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Recycled construction and demolition debris materials in roadway base/subbase applications

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RECYCLED CONSTRUCTION AND DEMOLITION DEBRIS MATERIALS IN ROADWAY BASE/SUBBASE APPLICATIONS

By

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Returning to New Hampshire for my Graduate work was one of the best decisions that Melissa and I have made. Thanks to everyone that made it so enjoyable.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ARAI	Applied Research Associates Incorporated
ASCE	American Society of Civil Engineers
ASR	Alkali Silica Reaction
ASTM	American Society for Testing and Materials
ASU	Arizona State University
C&D	Construction & Demolition
CBR	California Bearing Ratio
C_C	Coefficient of Curvature
C_U	Uniformity Coefficient
DCP	Dynamic Cone Penetrometer
DOT	Department Of Transportation
ERRCO	Environmental Resource Return Corporation
ETG	Expert Task Group
FEM	Finite Element Model
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
LOI	Loss On Ignition
LTPP	Long Term Pavement Project
LVDT	Linear Variable Differential Transducer

MaineDOT	Maine Department Of Transportation
MEPDG	Mechanistic Empirical Pavement Design Guide
M_R	Resilient Modulus
NCHRP	National Cooperative Highway Research Program
PID	Peak, Intensity, Duration
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregate
RMRC	Recycled Materials Resource Center
TRB	Transportation Research Board
UNH	University of New Hampshire
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
USGS	United States Geological Survey
WisDOT	Wisconsin Department Of Transportation
WMNHTREE	Waste Management of New Hampshire Turnkey Recycling and Environmental Enterprises

ABSTRACT

RECYCLED CONSTRUCTION AND DEMOLITION DEBRIS MATERIALS IN ROADWAY BASE/SUBBASE APPLICATIONS

By

Mark J. DeRocchi

University of New Hampshire, May, 2008

U.S. industries annually generate millions of tons of construction and demolition (C&D) debris with a large percentage sent to landfills at considerable cost and using valuable landfill space. While at the same time, according to the Department of Transportation, the U.S. requires about 500 million tons of materials annually for highway construction, rehabilitation, and maintenance. Recently more and more emphasis has focused on trying to meet the demand for highway construction materials by using C&D debris. Despite large use of construction debris in non-structural roadway applications, very little to none of this material is used for actual load bearing construction. This is mainly due to limited research and the lack of knowledge of the engineering properties of the debris materials.

This research focused on using the latest standards in roadway soil testing, the Resilient Modulus (triaxial test) and California Bearing Ratio, to

evaluate both local natural materials and C&D debris to determine the engineering properties of each material. Then, using the testing results, evaluate the performance of these materials with the Federal Highways Mechanistic-Empirical Pavement Design Guide software. Determining these properties and evaluating the performance will help to determine if New England C&D debris can meet the future needs of local roadway construction.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Providing high quality roadway construction material over the next two decades presents a significant engineering challenge. According to the Department of Transportation (DOT), the U.S. requires about 500 million tons of materials annually for highway construction, rehabilitation, and maintenance. As local borrow pits are expended, the transportation costs for high quality outlying base/subbase materials may become cost prohibitive. At the same time, U.S. industries generate 450 million tons of Construction and Demolition (C&D) debris annually with over 50% of the debris sent to landfills. Disposing of C&D debris comes at a considerable cost (tipping fees and transportation) and consumes valuable landfill space (Sandler, 2003). As landfills continue to close and restrict the materials deposited, the cost associated with landfill use will grow. Ideally, C&D debris could replace road construction materials, keeping construction costs reasonable while saving landfill space.

C&D debris has been used successfully in non-structural roadway applications, but very little to none of this material is used for actual load bearing construction. This is mainly due to inadequate research and limited knowledge of the engineering properties of debris materials.

This research focused on providing valuable insight for the possibility of meeting the demand for road construction material in the New England region with C&D debris.

1.2 Introduction and Background

Every year U.S. industries generate millions of tons of solid waste in the form of industrial by-products. Although some of these materials are reused in other projects, most of these materials are landfilled at considerable cost (Edil, 1998). Since the inception of modern environmental regulations, disposal of this industrial solid waste is a major problem due to shrinking landfill space, environmental hazards, and rising disposal costs (Vipulanandan and Basheer, 1998).

Recently, shifting societal attitudes have resulted in a stronger interest for the use of industrial by-products to prevent wasted landfill space. Some by-product items such as blast furnace slag, fly ash, and recycled asphalt pavement are used annually in very high percentages with little ending as landfill waste (Sandler, 2003).

The largest sector of industrial by-products, C&D debris, generates approximately 450 million tons annually. However, the vast majority of this by-product goes unused each year and therefore wastes millions of cubic yards of landfill space. (EPA Report 530-R-98-010, 1998) According to local C&D debris company Environmental Resource Return Corporation (ERRCO), this material goes unused each year because of its highly variable content and consequently variable engineering properties. Even though C&D debris is significantly cheaper than native virgin material, contractors are not willing to gamble the cost savings with potentially negative results. For that reason, most C&D debris terminates as landfill (ERRCO, 2007).

1.3 Construction and Demolition Debris

C&D debris is defined as "waste material that is produced in the process of construction, renovation, or demolition of structures" (Sandler, 2003). Figure 1.1 shows the average national C&D debris generated in 2003.

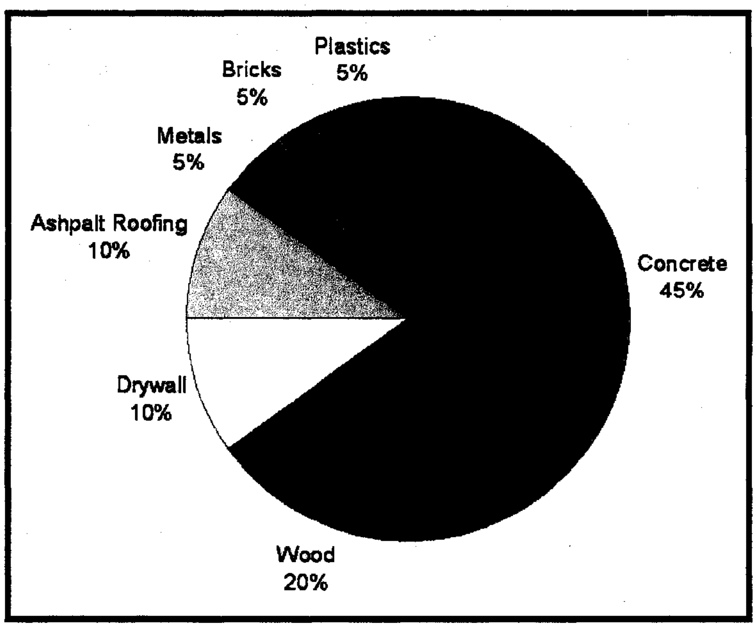


Figure 1.1: 2003 National C&D Debris Average (Sandler, 2003)

One way to make C&D debris more useful is to reduce the inherent variability. By separating the variable C&D debris stream into more consistent sources of material, it is possible to produce a locally reusable product. Many small companies like ERRCO are experimenting with that exact business model. In the New England area, many items in the C&D debris stream are already accounted for after separation. Scrap metal is bought by an east coast foundry; wood material is chipped and bought by a power company in Maine; while plastics are sold for recycling (ERRCO, 2007). Still other materials are removed to prevent possible hazardous conditions. Material like drywall can generate hydrogen sulfide gas under the right conditions and is presently removed from the C&D debris stream. Currently, the University of New Hampshire's (UNH) Recycled Materials Resource Center (RMRC) is investigating this concern and researching possible future solutions (RMRC, 2007).

Considering the categories of Figure 1.1, the only construction materials left unaccounted for is concrete and brick. That is more than 50% of the total C&D debris unused annually. As previously mentioned, this material currently goes unused because its properties vary from each point-source. At this time, the most practical local option is to blend this stream annually at the regional level and provide a semi-homogenous product (ERRCO, 2007).

1.4 Thesis Objectives and Experimental Approach

The goal of this project was to investigate the use of C&D debris in roadway base/subbase application, through testing and model simulation, and then compare the results with known successful materials in the New England region. This research focused on using the latest standards in roadway soil testing, the California Bearing Ratio (CBR) and the Resilient Modulus (M_R), to evaluate local natural material and local C&D debris and determine the engineering properties of each material. Using the test results, the performance of these materials were evaluated with the Federal Highway Administration's (FHWA) Mechanistic-Empirical Pavement Design Guide (MEPDG) software. Determining these properties and evaluating the performance will help to evaluate if New England C&D debris can meet the future needs of local roadway construction.

This research was divided into three stages. The first stage focused on establishing an in-house laboratory protocol to effectively test local materials to determine the engineering properties with high repeatability while also reproducing results from other laboratories. The second stage of this research focused on testing local construction debris using the same standards established in the previous testing. The final stage focused on using the results from stage one and stage two in the same hypothetical design model to evaluate the comparative performance of each material.

Research for this project included the following tasks:

- Determine Material Properties
- Conduct California Bearing Ratio Test
- Perform Resilient Modulus Procedure
- Evaluate American Association of State Highway and Transportation Officials CBR → M_R Model
- Evaluate Long Term Pavement Performance M_R Model

- Determine Effects of using CBR or MR with Mechanistic-Empirical Guide
- Assess the possibility of Construction and Demolition Debris in Base / Subbase Applications

These research tasks will provide the data needed to determine if New England C&D debris could meet the future needs of local roadway construction.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

In the 1970s, early recycling efforts identified the possibility of using landfill solid waste for use in roadway construction as a way of reducing soaring landfill usage. For a multitude of reasons, these projects were not a properly controlled use of solid waste and became known as linear landfills. Using C&D debris as part of roadway construction should not be confused with the linear landfill concept. The possible use of C&D debris is instead a process of selecting high quality material from the solid waste stream, removing it to prevent landfill occupation, and further gaining engineering benefit with the same material (Cosper et al., 2004). Using industrial by-products to replace natural soils, aggregates, and cements can be highly desirable. While in some cases a by-product is inferior to natural earthen materials, its lower cost makes it an attractive alternative if adequate performance can be obtained (Edil and Benson, 1998). Although many DOTs currently use Recycled Concrete Aggregate (RCA), this is vastly different from using recycled concrete from the C&D debris stream. While meeting all of the 500 million tons of material needed for annual roadway construction, rehabilitation, and maintenance with recycled materials is unlikely, by using C&D debris whenever feasible, it is possible to replace some of the demand and reduce landfill use at the time same time.

2.1.1 Landfill Versus Local C&D Debris

Based on data collected in December of 2007, the local tipping fee for construction and demolition debris for town disposal in Lee, New Hampshire was $85 per ton (Hoyt, 2007). Despite the ease of using town disposal, most contractors instead tip at the regional Turnkey landfill. With a required minimum annual contract, the bulk-tipping fee at Waste Management of New Hampshire, Turnkey Recycling & Environmental Enterprises (WMNH-TREE) in Rochester, New Hampshire was $55 per ton (Whittier, 2007). With a similar annual contract, but additional strict dumping regulations, the bulk-tipping fee at ERRCO in Epping, New Hampshire was $35 per ton (ERRCO, 2007).

At some point in the near future, the rising cost of local disposal will naturally drive contractors to seek more recycling opportunities. The current $35 per ton and very strict requirements has most contractors still using the Turnkey landfill for their C&D debris over ERRCO. The savings of $20 per ton is currently not enough incentive to overcome the additional regulations.

As the market for recycled materials grows stronger, ERRCO will be able to either reduce their tipping fee or increase their recycled material input stream allowing more recycling. Presently, the aggregate material is stockpiled for future use. This aggregate material consists mainly of recycled concrete and is the largest percentage of the C&D stream. Of all the C&D materials, this has the greatest potential for future roadway construction, while at the same time reducing landfill use.

2.2 Recycled Concrete

Billions of tons of concrete have been used since World War II to construct buildings, bridges, dams, roads, and other structures. When the useful life of these structures is over, the materials from which they were built will eventually find their way into the C&D debris waste stream. The demolition of these roads and structures generate more than 200 million tons of recycled concrete and asphalt annually that can be used for recycled aggregate (USGS Fact Sheet, 2000).

The idea of using recycled concrete to replace natural virgin aggregates is not a new concept. In 1997, Vanderbilt University conducted a survey of North American industries and determined that 32 states were using recycle concrete at that time. Since the United States Army Corps of Engineers (USACE) first conducted testing of RCA for use in base/subbase construction in 1960, an estimated 85% of all recycled concrete nationwide is used as road base due to its availability, cost, and physical properties (Cosper et al., 2004).

Due to the many benefits achieved from using recycled materials, and the vast amount of waste concrete generated annually, maximum utilization of the waste concrete should be the primary concern (Tandon and Picornell, 1998). Since vast amounts of energy go into making cement and concrete in the first place, secondary applications could have huge economic benefits. Additionally, using all forms of recycled concrete has tremendous potential for the construction industry (Melton, 2004).

2.2.1 RCA Versus C&D Debris Concrete

While there is little question of the benefit of high quality recycled concrete, RCA is traditionally hand-selected prior to demolition and identified for a specific construction demand. Conversely, the concrete that is available in the C&D stream is not always high quality concrete and is subject to extreme variability based on location of origin. Producing a steady source of high quality RCA from the C&D debris stream is simply not possible. Not only does the origin of the demolition project change with each load of C&D debris, but also the original quality of the concrete that is recycled. In addition, wood particles, brick particles, and glass particles are ubiquitous in the C&D debris stream (Sandler, 2003). Therefore, despite hand selection, concrete from the debris stream will always result in unwanted materials, which is very different from using RCA (ERRCO, 2007).

Despite great success in the field using RCA, the ability to properly design for its use is still not adequate due to limited experience. USACE studies conducted on RCA identified many concerns when using 100% RCA in roadway applications. Consequently, USACE established maximum RCA percentage recommendations for use in different applications from concrete work to roadway construction (Cosper et al., 2004). However, this only shows that more research must be done to understand the properties of recycled concrete.

Problems notwithstanding, there is still a large amount of recycled concrete available annually from the C&D debris stream. Getting the most out of this recycled concrete is an important step to preventing the overuse of natural supplies. Long-term successful use of C&D debris in roadways will also help limit overuse of landfills.

2.2.2 Concrete Concerns

One negative side effect of using RCA or C&D debris concrete is its premature deterioration due to Alkali Silica Reaction (ASR). ASR can cause volumetric expansion, which increases internal fracturing and decreases overall lifespan and strength (Gress, 2007). For that reason, ASR is of concern in the New England region. The potential for deterioration should be evaluated through testing before use. Currently, this long-term aspect of the recycled concrete waste stream is under evaluation by Dr. David Gress (RMRC, 2008).

Another concern of using concrete recycled from the C&D debris stream is hazardous leachate. Whether this leachate is hydrogen sulfide or other oxides (SiO_2, Al_2O_3, and CaO) from the concrete, increased use of recycled concrete has shown an increase in these by-products. Studies underway at Kingston University in England are evaluating effective ways to mitigate this concern (Limbachiya et al., 2006).

In addition, when recycled concrete (RCA or C&D debris) is used in unbound applications, increased pH of runoff can be a concern. Rainwater moving through the material may rise to a pH of 12 and adversely affect the surrounding environment. Careful consideration must be used before using this type of material where water intrusion is expected. Environmentally responsible locations should be selected as part of the design process (Melton, 2004).

2.3 Industrial By-Product Planning

Regardless of the material being used, the American Society of Civil Engineers (ASCE) recommends the following nine steps in the development of industrial by-products for use as geotechnical materials (Edil and Benson, 1998).

1) Identification of the application
2) Selection of the key properties required for the application
3) Environmental suitability
4) Laboratory testing protocols
5) Modeling of engineering behavior
6) Constructability and field verification of performance
7) Construction specifications
8) Long-term performance
9) Dissemination of technical information

It is generally recognized that the utilization of recycled materials in civil engineering construction, such as highway pavement, is a promising concept from both environmental and economic standpoints. There are in-use roadway case studies currently underway around the U.S. to determine long-term performance and gather field data. However, at issue is how to characterize the candidate waste materials, as this is necessary to assess their suitability as a component in the pavement structure (Sobhan and Krizek, 1998).

With the ASCE nine-step process, the use of C&D debris for roadway base/subbase is step one. Step two, select key properties required, should therefore be the same as with all roadway base/subbase materials and is determining the material strength. With environmental studies underway at the RMRC and Kingston University, step three is being addressed for areas where those environmental concerns apply. Therefore, the main effort of this research focused on steps four and five, the laboratory testing protocols and modeling of engineering behavior. Hence, the next area of concern is to determine laboratory testing protocols (RMRC, 2008; Limbachiya et al., 2006).

The laboratory testing protocols should not be specific to C&D debris, but rather standardized tests used for all roadway base/subbase materials. Because this material would be used in public roadway construction, it would be subject to current guidelines. Therefore using the standard tests identified by the American Association of State and Highway Transportation Officials (AASHTO) is the place to begin.

According to the AASHTO standards, the California Bearing Ratio (CBR) and Resilient Modulus (M_R) are the two tests present to assess the strength and suitability of coarse-grained materials for roadway use. Understanding that recycled concrete can serve as base/subbase material successfully in field-testing, it is unknown if the CBR and M_R tests can be effective for design purposes as with current soil testing. AASHTO Standard Specifications for

Transportation Materials and Methods of Sampling and Testing (Volumes 2A and 2B) cover both CBR and M_R testing in Soils and Stabilization standards (AASHTO, 2008). However, before starting at the current procedures for CBR and M_R, it is important to understand how the industry standard arrived there.

2.4 Laboratory Protocols

2.4.1 Protocol Background

The National Cooperative Highway Research Program (NCHRP), a subcommittee of the Transportation Research Board (TRB), recommends all public roadway systems operate in compliance with current AASHTO or ASTM standards (NCHRP Bulletin, 2001). For the purpose of this research, all tests, not just the CBR and M_R, will therefore be conducted in compliance with AASHTO standards so that results may be used by local Highway Departments in the region. It is important to note that although the two states that donated material, New Hampshire and Maine, have not purely adopted these standards for their programs, both DOTs consider AASHTO standards to meet or exceed their current testing requirements. Chapter 3, Methods and Materials, covers the actual AASHTO standards used for each research objective.

2.4.2 Long Term Pavement Performance

The Long-Term Pavement Performance (LTPP) program is a 20-year study of pavement performance and the factors that affect it sponsored by the NCHRP. Its main goal is to provide the data necessary to explain how pavements perform and why they perform as they do. To meet this goal, the program established 2,500 test sections on in-service roadways throughout North America in 1988. The data collected from these sites is intended to characterize pavement performance nationwide. In the case of unbound materials, the most important data elements are CBR and M_R. Currently, M_R is also one of the most controversial because of highly variable results. A 25% deviation in M_R results was found during LTPP testing. However, the M_R value is the key input for unbound layers in the current NCHRP design procedure. Therefore, the M_R ultimately correlates to the foundation strength, and therefore long-term pavement performance (Rada et al., 2003). Section 2.5 covers CBR while Section 2.6 covers the M_R.

2.5 California Bearing Ratio

The CBR is a soil strength test established by the California Highway Department in the 1940s. It was established in response to the need for a standardized test to evaluate the strength of natural in-situ materials. The test uses materials that have been prepared at maximum dry density and optimal water content. Following preparation, the compacted sample is then soaked for 96 hours to represent a saturated condition. Then, using a standard circular plunger of three square inches, the material is deformed at a constant rate of 0.05-inches per minute. The required stress to achieve 0.1-inches and 0.2-inches of deformation is reported by recording the stress and strain of the material during the testing. After normalizing these results to high quality fill, the bearing ratio is reported as a percent.

The CBR is an inexpensive, simple, highly repeatable, and highly reproducible strength test designed for subgrade material. The ease-of-use and its ability to be conducted in the field or laboratory made this test extremely popular. Due to its popularity, the CBR also became the standard for base and subbase materials during the 1960s. Consequently, from the 1940s until the 1980s, the CBR was the standard-bearer and only nationally recognized test for subgrade, base, and subbase materials. Equation 2.1 shows the CBR formula (AASHTO, 2008).

$$CBR = \frac{\sigma_1 (at \Delta_V = 0.1'' Corrected)}{1000[psi]} \quad \text{(Equation 2.1)}$$

$CBR =$ California Bearing Ratio [%]

$\sigma_1 =$ Principal Stress (vertical) [psi]

$\Delta_V =$ Vertical Deformation [inches]

The standard procedure and required method of testing for the CBR is published as AASHTO designation T-193. This test method covers determination of the CBR of pavement subgrade, subbase, and base course materials from laboratory compacted specimens.

The CBR was easily repeated and reproduced, therefore making it extremely useful during a rapidly growing period in highway transportation. However, pavement thickness was based empirically on local experience, soil classification, and response of the pavement to the CBR static load. A minimum thickness for a surface course was often selected based on plastic deformation as the only failure criteria and CBR as the only test (Vinson, 1998). Consequently, roadway failure occurred not with respect to the plastic deformation, but rather serviceability problems such as rutting and cracks.

During the 1970s as roadway use soared to record highs, the need for more complex design criteria became apparent. The bearing ratio was a great standard for comparing materials, but it did not directly correlate to roadway design and construction. By designing with only bearing ratio, elastic deformations were not even considered (Vinson, 1989).

In general, static testing procedures are not adequate for determining the behavior of soil and aggregate materials subjected to the impulse type repeated loading representative of moving wheel loads (The Aggregate Handbook, 1993). In recent years, pavement engineers have recognized cyclic load triaxial tests as a fundamental mechanism for evaluating aggregate base and subbase soils (Papp et al., 1998).

At the same time, the ability to use computers and collect high volume data offered the opportunity for more complex testing. Additionally, as computers became faster, the ability to accurately monitor samples and control servo values by computer became standard in the laboratory. These two fundamental changes set the stage for modulus of resiliency testing.

2.6 Resilient Modulus

The M_R is the ratio of applied axial stress to the recoverable axial strain. Equation 2.2 defines the Modulus of Resiliency and is used to calculate M_R.

$$M_R = \frac{\sigma_d}{\varepsilon_R} \qquad \text{(Equation 2.2)}$$

M_R = Resilient Modulus

σ_d = Deviatoric Stress

ε_R = Resilient Strain

2.6.1 Resilient Modulus Background

Research conducted in the 1970s concluded that the true behavior of soils under traffic loading could only be obtained from repeated load tests. It was also noted that vehicle speed and depth beneath the paving surface are of great importance in selecting the appropriate compressive stresses. Using research obtained by the California Department of Highways, the relationship of vertical stress, vehicle velocity, and depth of sample were established (Vinson, 1989).

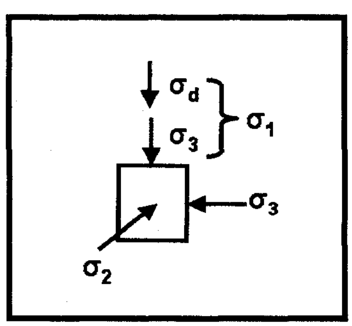


Figure 2.1: Generic Triaxial Stress Configuration

A confined triaxial test was selected as the base model to replicate this soil behavior below the asphalt layer by AASHTO. The generic stresses present in a triaxial test configuration are shown in Figure 2.1.

Using the triaxial system, the effects a finite element experiences are modeled by the principal stresses. The surrounding soil stress is replicated with confining pressure (σ_2 and σ_3 in Figure 2.1) while vehicle load is replicated with a component of the vertical principal stress (σ_d in Figure 2.1). Furthermore, the stresses of a vehicle in motion are replicated with a change in amplitude of σ_d over time modeled by a haversine load. Figure 2.2 is an example of this modeled stress change and shows how σ_d changes over a period of 0.1-seconds.

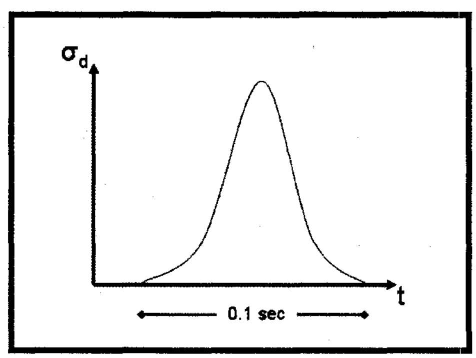


Figure 2.2: Triaxial Haversine Load Example

Using the 0.1-second load cycle repeatedly with a 0.9-second pause between load cycles is used to replicate traffic conditions in roadway applications. Figure 2.3 shows a generic load sequence for the repeated loading model.

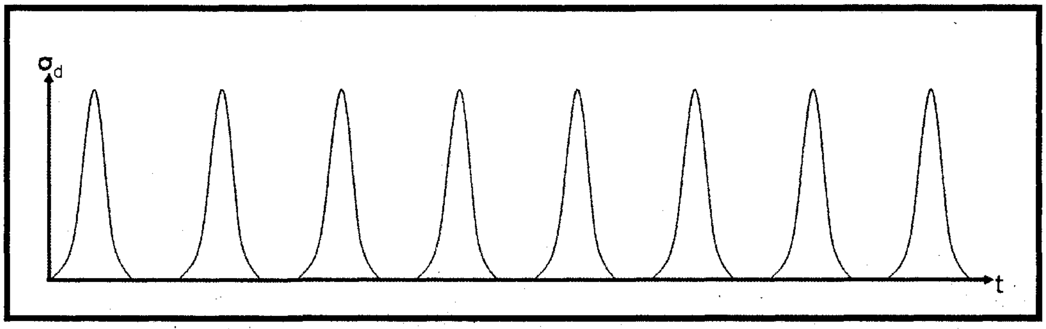


Figure 2.3: Repeated Triaxial Load Sequence

The M_R test was aimed at accurately modeling long-term elastic behavior of a finite element in any roadway surface. In addition, testing through a range of confining pressures and various deviator stresses would provide a battery of tests that represented a wide range of real world conditions during a roadway's useful lifespan.

2.6.2 History of Resilient Modulus and LTPP

One lesson learned shortly after the implementation of the first M_R test was not to assume that properly operating equipment and knowledgeable personnel imply good M_R data (Durham, 2003). The resilient modulus test is far more difficult than anyone first anticipated and the first M_R standard (1987) contained too great a risk of potential variability because of its wording. As such, the LTPP established an Expert Task Group (ETG) dedicated to producing a new procedure for testing and revise the current M_R protocols. In 1989, the ETG produced the first revision of the M_R standards. Consequently, AASHTO discontinued M_R tests T-274, T-292, and T-294 (each with different pre-conditioning standards) in 1990 (Chen et al., 1994).

Later that same year the LTPP program compiled and issued a new testing protocol, NCHRP Protocol 46. Four laboratories tested the updated protocol and recommended further changes. In 1992, the LTPP issued a revised Protocol 46 (Groeger et al., 2003). The 1992 version remained for 4 years, when in 1996 another significant review and revision took place. Based on the 1996 version, AASHTO evaluated and further revised the standard. They designated this latest protocol as AASHTO test T-307 in 1999.

Despite the various revisions, testing repeatability and reproducibility remain nationwide problems to this day. Currently, there are still annual meetings held by AASHTO, NCHRP, and other agencies, to provide insight for successful testing. The LTPP has recommended refining the laboratory startup procedures and identifying quality control checks to allow the tester confirmation of an acceptable specimen and valid testing results (Rada et al., 2003). However, to date, those recommendations still have not been adopted.

At the same time LTPP was working to modify Protocol 46, NCHRP Project 1-28 was also working on enhancements to increase precision, accuracy, and practicality of the existing methods. This project was contracted to Georgia Tech Research Corporation in 1990 and numerous modifications were recommended at the conclusion of the program in 1997 (TRB, 1998).

However, by the conclusion of the research, AASHTO had already completed review of Protocol 46. Consequently, NCHRP Project 1-28A was created to harmonize findings from NCHRP Project 1-28 and the AASHTO M_R review. The project was contracted to the University of Maryland in 1998 and found that "inaccurate determination of M_R in unbound materials will contribute to erroneous predictions of overall pavement response" (TRB, 2004). However, the findings were not presented until 2004 and, as a result, AASHTO decided to formalize the M_R in 1999 as test T-307 without the findings and despite concerns of accuracy and precision (Rada et al., 2003).

2.6.3 AASHTO Standards for Resilient Modulus

After Protocol 46 was balloted through the AASHTO process, it was adopted as test T-307: Determining the Resilient Modulus of Soils and Aggregate Materials. Quoted from the AASHTO Standard Specifications for Transportation Materials and Methods for Sampling and Testing, "this method covers the procedure for preparing and testing untreated subgrade soils and untreated-base/subbase materials for determination of M_R under conditions representing a simulation of the physical conditions and stress states of materials beneath flexible pavements, subject to moving wheel loads."

The M_R indicates the stiffness of a soil under controlled confinement conditions and repeated loading. The test is intended to simulate the stress conditions that occur in the subgrade and base/subbase of a pavement system. M_R has been adopted by the U.S. Federal Highway Administration (FHWA) as the primary performance parameter for pavement design (Durham, 2003). Table 2.1 shows the complete 16 cycles required for base/subbase testing by AASHTO standards while Figure 2.4 shows the same stresses graphically with Mohr's Circle.

Sequence Number	Confining Pressure $\sigma_2 = \sigma_3$ (kPa)	Maximum Axial Stress σ_d (kPa)	Cyclic Stress σ_{cyclic} Portion of σ_d (kPa)	Constant Stress Portion of σ_d (kPa)	Load Cycles (#)
(0) Condition	103.4	103.4	93.1	10.3	500-1000
1	20.7	20.7	18.6	2.0	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

Table 2.1: Base/Subbase Resilient Modulus Testing Procedure

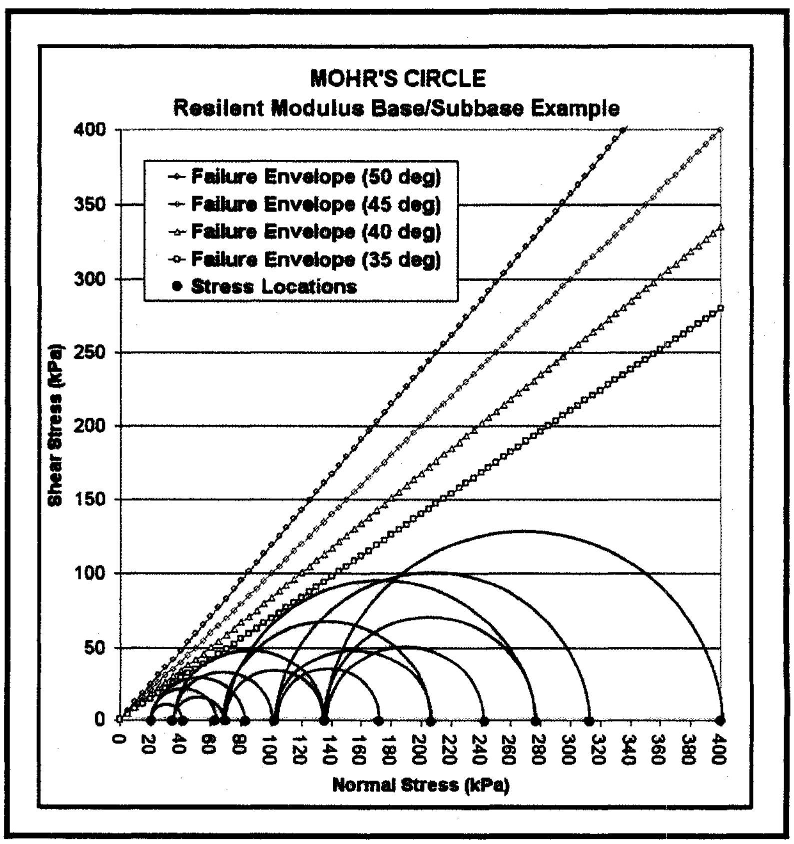


Figure 2.4: Mohr's Circle for Base/Subbase M_R Testing Procedure

Just as bearing ratio testing focused on plastic deformation, test T-307 focuses on long-term elastic behavior (i.e. after permanent deformation and consolidation occurres and before the plastic strain condition). Consequently, the protocol uses a conditioning cycle, Cycle-0, of 500 to 1000 load repetitions to pre-condition the sample to ensure consolidation and eliminate permanent deformation prior to testing. The sample is then tested in the elastic, or resilient, state.

Figure 2.5 shows the expected strain types for each sample. A sample is loaded numerous times and hysteresis loops are shown for cycles a through f. There is permanent deformation (unrecoverable strain) due to the early cycles. Once this deformation has occurred, there is elastic strain and recovery. Past the elastic strain region, is plastic strain provided the stress applied will cause the required material change.

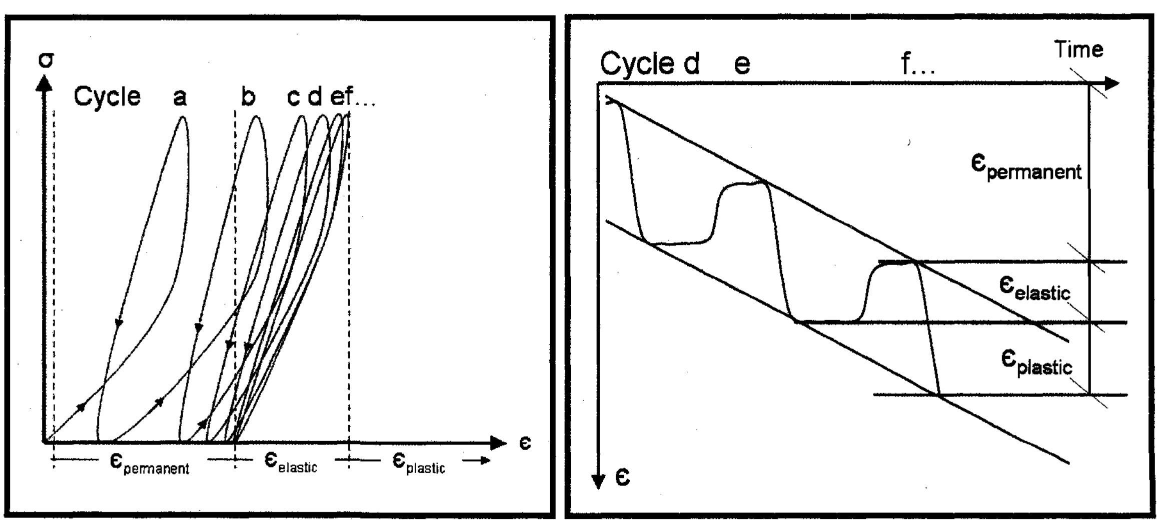


Figure 2.5: Strain Regions of Generic Sample

Because the M_R focuses on the elastic strain, the 500 to 1000 cycles of pre-conditioning ensure the sample is in this region during recorded tests. The test protocol gathers data to calculate the modulus of resiliency as the elastic region is the state where the sample rebounds or has resilience. Evaluating the material strength in this region provides valuable insight to the materials long-term behavior as roadway base/subbase and therefore rutting and cracking of the road surface. Table 2.2 highlights the protocol specifications for the AASHTO standard required to achieve the M_R results. The M_R determined from this procedure is a measure of the elastic modulus and designed to provide input for structural analysis models and for use in pavement design procedures. Additional detailed information about test requirements is available in AASHTO Standard Specifications Volume 2B.

Protocol Specification	AASHTO T-307
Loading System	Hydraulic / Pneumatic
Load Control	Closed Loop
Load Cell Location	External
Deformation Measurement	External LVDT (2)
Confining Fluid	Air
Load Pulse Shape	Haversine
Load Duration	0.1 seconds
Cycle Duration	1.0 to 3.0 seconds
Data Points per Cycle	200
Specimen L/D Ratio	2:1
Compaction	Static / Vibratory / Kneading
Pre-Conditioning	500 to 1000 cycles

Table 2.2: T-307-99 Protocol Specifications

While Equation 2.2 defined M_R, Equation 2.3 describes the value of M_R calculated by the AASHTO standard and is used to determine the empirical resilient modulus. Unlike Equation 2.2, this M_R is based on numerous data points for each stress combination, and not just one set of stress-strain.

$$\overline{M}_R = \frac{\sigma_{dh}}{\varepsilon_R} \qquad \text{(Equation 2.3)}$$

$\overline{M}_R$ = Empirical Resilient Modulus (Average of cycles 95-100)

σ_{dh} = Haversine Deviatoric Stress (cycles 95-100)

ε_R = Resilient Strain (cycles 95-100)

By using five cycles of data, instead of just one, the reported AASHTO M_R value more accurately represents the soil by using numerous collected data rather than one random result. In addition, the tester uses cycle 1 through 94 to fine tune the loading sequence to ensure cycle 95 through 100 accurately represent the required loads. Combining these changes, ensure more reliable and repeatable results that accurately reflect the soil strength.

2.6.4 Repeatability Problems with Resilient Modulus

Shortly after AASHTO adopted the modern standard for M_R testing, the University of Oklahoma conducted a study to determine the variability of aggregate materials (less than 10% passing #200 sieve). Their testing found that variability of M_R ranged from 19% to 26% (Chen et al., 1994). Since the release of that study in 1994, vast research has been dedicated to increasing the repeatability of M_R, with many recommendations making their way into the latest protocol.

A detailed review of nationwide M_R test data by the LTPP ETG showed that test results could be highly affected by sampling technique, testing procedure, and specimen errors. Specimen errors included leaks in membrane, unstable Linear Variable Differential Transducers (LVDT), incorrect conditioning sequence, and specimen disturbance. Recommendations included quality control checks and placing the load cell and LVDTs inside the triaxial chamber instead of outside the chamber as required by testing procedures (Groeger et al., 2003).

The focus of revisions and amendments to the M_R testing procedures have been aimed at increasing the repeatability of the results. Despite the revisions adopted by test T-307, the M_R test is still an extremely user sensitive procedure. In 1998, round robin proficiency tests concluded that even with the updated standard, performing a test cannot provide reliable test data to base a structural pavement design. The research suggested M_R variations as high as 26% at any given stress level. The conclusion of the proficiency tests recommended that two or three replicated specimens for each material should be used to accurately characterize the modulus of resiliency (Boudreau, 2003).

Research conducted industry wide, including current ongoing symposiums, have focused on increasing the repeatability of the modern M_R test. Experiments conducted from 2000 to 2002 by Boudreau Engineering identified some of the main failure areas in current M_R testing protocols. This testing determined some of the areas of concern are in the compaction methodology, the hydraulic servo, LVDT placement, and system calibration (Boudreau, 2003).

Boudreau Engineering concluded that when specific attention is paid to these problematic areas, and a test is rerun after identifying a problem, AASHTO test T-307 produced repeatable results.

From studies conducted before the Boudreau research, LTPP team leader Aramis Lopez conducted research focusing on increasing the repeatability of the M_R. Lopez recommended a series of checks to perform during and after testing to act as a quality assurance and quality check. His checks include:

1) Load Pulse Reasonableness Check
2) Deformation Response Reasonableness Check
3) Confining Pressure Conformity
4) Sample Integrity
5) Post Processing Test Result Checks (Lopez et al., 1994)

In summary, the high variability of the M_R tests results from three independent testers suggest additional steps, quality checks, and replicated specimen testing are needed to ensure repeatable results with the current state of practice for M_R testing. Chapter 3 addresses the actions taken during this research in light of these recommendations.

2.6.5 Prediction Models for Resilient Modulus

The LTPP conducted a study of M_R test data and response characteristics in 2002. The summary report of this study documented the first comprehensive review of resilient modulus test data and presented the results of each major soil type. The testing data were investigated to evaluate relationships between M_R

and properties of the unbound materials. Using a national database of 4,000 plus M_R tests, the panel selected 2,014 tests that passed all quality control checks. After refining the data sets, the panel further removed 94 tests with potential errors ensuring the remaining data sets were of the highest quality. Once confirmed that all data sets were free of errors, the test data was studied for the effect of sampling procedure on the M_R and further investigated to evaluate the relationship between M_R and the physical properties of the unbound material.

Despite earlier findings (Section 2.6.4), sampling technique was found to have little or no effect on base/subbase M_R, and more importantly, regardless of sampling technique, if the dry density (γ_{dry}) was within ±3% of maximum dry density (γ_{max}) than the samples density had little or no effect on the sample M_R.

Panel members Von Quintus and Killingsworth found that the universal constitutive equation, Equation 2.4, provided a very good fit to the LTPP test data.

$$M_R = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sigma_d}{P_a}\right]^{K_3} \quad \text{(Equation 2.4)}$$

$M_R =$ Resilient Modulus [MPa] from Universal M_R Equation

$P_a =$ Atmospheric Pressure [kPa]

$\theta = (\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d) =$ Bulk Stress [kPa]

$\sigma_d = \sigma_1 - \sigma_3 =$ Deviatoric Stress [kPa]

$K_1, K_2, K_3 =$ Regression Constants [no units]

The regression analysis of the tests showed K_1 is proportional to Young's Modulus. Thus, the values for K_1 must be positive. Increasing the bulk stress produces a stiffening effect that yields a higher M_R and therefore K_2 must be positive. Increasing the deviator stress increases the vertical strain and therefore lowers the M_R. Consequently, K_3 must be negative. After conducting the regression on all 1920 data sets, the panel published the results for K_1, K_2, and K_3 ranges for their data. These results can be found in Table 2.3.

In addition, the panel broke down the materials by type and reported the regression analysis. The reported values for K_1, K_2, and K_3 for their base/subbase material are shown in Table 2.4.

	Min	Max
K1	0.00	3.00
K2	0.00	1.50
K3	-7.00	0.00

Table 2.3: K_1, K_2, and K_3 Regression Value Range All Samples (Yao and Von Quintus, 2002)

	Min	Mean	Max
K1	0.28	0.87	1.85
K2	0.17	0.63	1.06
K3	-2.80	-0.17	0.05

Table 2.4: K_1, K_2, and K_3 Regression Value Range for Base/Subbase (Yao and Von Quintus, 2002)

Von Quintus and Killingsworth later investigated an expanded version of the M_R equation to consider if the expanded version was a better fit than the universal version. Equation 2.5 lists the M_R expanded version.

$$M_R = K_1 P_a \left[\frac{\theta - 3K_6}{P_a}\right]^{K_2} \left[\frac{\tau_{OCT}}{P_a} + 1\right]^{K_3} \qquad \text{(Equation 2.5)}$$

M_R = Resilient Modulus [MPa] from Expanded M_R Equation

$\tau_{OCT} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$ = Octahedral shear stress [kPa]

K_6 = Additional regression constant [no units]

The panel found that K_1, K_2, and K_3 performed in the same manner as with the universal equation. The variable K_6, which was intended to account for porewater pressure or cohesion, was found to be zero for more than 50% of all 1920 tests. K_6 was also found to be equal to zero for 74% of base/subbase materials due to minimal cohesion and absence of porewater pressure in that type of soil. In addition, the range and mean value of K_2 had no significant change. Furthermore, the value of K_3 did not change because in a triaxial test the octahedral shear stress is directly proportional to the deviator stress when confining stress is uniform ($\sigma_2 = \sigma_3$). Equation 2.6 shows the relationship between octahedral shear stress and deviator stress in triaxial testing.

$$\tau_{OCT} = \frac{\sqrt{2}}{3}\sigma_d \qquad \text{(Equation 2.6)}$$

when $\sigma_2 = \sigma_3$ and $\sigma_1 = \sigma_d + \sigma_3$

Therefore, K_6 was set at zero and the regression repeated. No significant effect was observed on the regression statistics. Consequently, with respect to the M_R test, both the universal and expanded equations are accurate for modeling because when simplified and reduced the equations are approximately equal. Upon completion of analysis, the LTPP recommended a modified equation, Equation 2.7, as the most appropriate empirical model for the current resilient modulus test procedure. This final version of the M_R is known as the modified universal equation (Yao and Von Quintus, 2002).

$$M_R = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\tau_{OCT}}{P_a}\right]^{K_3} = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sqrt{2}}{3}\frac{\sigma_d}{P_a}\right]^{K_3} \qquad \text{(Equation 2.7)}$$

The final LTPP report for base/subbase materials also established an appropriate range, mean value, and statistical data for the K_1, K_2, and K_3 variables. While Table 2.3 listed the range and mean value for base/subbase materials, the actual statistical data for the regression constants is available in FHWA's final report numbered RD-O2-051 dated October 2002.

After regression analysis of the data, the panel identified any possible anomalies that may have passed the initial quality and control checks. If the R^2 value of the regression was <0.99 and standard error was greater than 50% than the data was flagged for further review. Of the 212 flagged data sets, 185 tests were considered to have potential anomalies and removed from the evaluation. After completing analysis, the panel concluded that with all possible irregularities removed, the modified universal equation model characterized the M_R response for almost 92% of data sets (Yao and Von Quintus, 2002).

With the modified equation and appropriate K-values for each material subgroup, the LTPP panel reported the model fit of predicted M_R versus actual M_R for all tests evaluated (i.e. clay, crushed stone, sand, etc.). Figure 2.6 is an example of the actual M_R versus predicted M_R results for the crushed stone presented in the LTPP report.

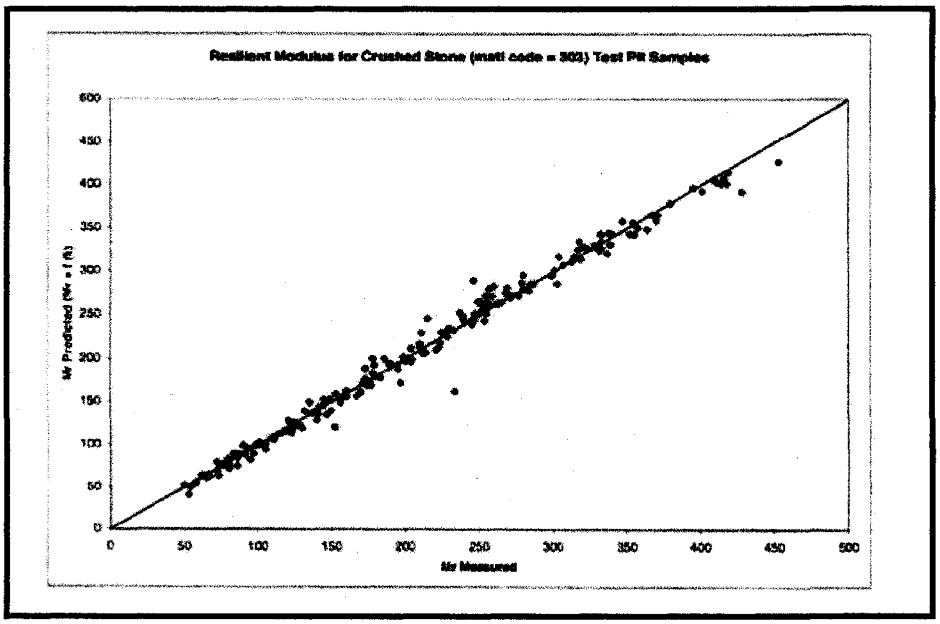


Figure 2.6: Actual M_R versus Predicted M_R for Crush Stone

Because of the detailed LTPP study and decidedly well fit modified model, the National Cooperative Highway Research Program (NCHRP), adopted the LTPP modified equation as the preferred input for the Mechanistic-Empirical Pavement Design Guide (MEPDG) in 2002. Based on the LTPP analysis, NCHRP established the use of K-values to model the soil only if regression resulted in R^2 values of >0.90. If the R^2 does not exceed this value, the test results and equipment should be checked for possible errors. If no errors or disturbances are found, the use of a different relationship should be considered (Yao and Von Quintus, 2002).

The modified universal equation is a best-fit model for over 2000 M_R tests. Of those tests, 90% were fine-grained materials. Therefore, as stated in the objectives, this research will investigate the effectiveness of using Equation 2.8 to predict M_R based on stress conditions for the coarse-grained materials that often makeup base/subbase fill.

2.6.6 Modeling Resilient Modulus with California Bearing Ratio

Due to the complex nature and expensive costs of resilient modulus testing, AASHTO identified the need for correlation equations from current standardized testing to predict M_R for use in the new design guide. Because of its wide use and popularity, a correlation between the CBR and M_R was needed. Using data collected for the 1993 AASHTO guide, Equation 2.8 became the modified standard to relate known CBR values to predicted M_R values.

$$M_R = 2555(CBR)^{0.64} \qquad \text{(Equation 2.8)}$$

$M_R =$ Resilient Modulus [psi] from CBR to M_R Conversion

$CBR =$ California Bearing Ratio [%]

Understanding this correlation is the best-fit model for a wide range of soil types, it is not meant to serve as an exact correlation for specific types of materials. Use of engineering judgment and confirmation tests are recommended as part of the 2002 design guide (NCHRP, 2004). As stated in the objectives, this research will investigate the effectiveness of using Equation 2.8 to predict M_R based on CBR values for base/subbase fill.

2.6.7 Resilient Modulus and the Pavement Design Guide

Once NCHRP selected the M_R test, modified universal equation, and K-values as the highest standard for input into the pavement design guide, DOTs around the country focused their research on evaluating the model and determine if it should be adopted. One state in particular dedicated vast resources to evaluate their soils using this new system.

Wisconsin DOT (WisDOT) took 17 commonly used subgrade materials and conducted extensive M_R research. However, after testing WisDOT found the M_R to require such specialized training, expensive equipment, and vast amounts of time that alternate correlations to estimate M_R from basic soil properties became their primary goal (Titi et al., 2006).

Their first attempt to analyze the M_R data with the modified universal equation produced poor correlations and the modeled values did not adequately predict actual M_R. Another attempt at regression was made by separating fine and coarse-grained samples and reanalyzing. The fine-grained materials fit much better and produced R^2 values of 0.95, 0.76, and 0.65. However, the coarse-grained soils (less than 50% passing #200 sieve) still resulted in poor correlations (Titi et al., 2006). This finding is very important, as the base/subbase materials used in this research have even less percentage passing the #200 sieve compared to the WisDOT coarse-grained materials.

2.7 Pavement Design Guide

2.7.1 Pavement Design Guide Background

From 1960 to 1996, AASHTO published numerous versions of a guide to assist with design of pavement structures. During that time, the design of pavement was based on empirical equations derived from the AASHTO road test in 1958. In 1996, recognizing the need for a joint mechanistic and empirical design guide, NCHRP, a subcommittee of the TRB, started Project 1-37A. The project focused on the successful delivery of a mechanistic-empirical pavement design guide to serve as the standard for all future design guides. NCHRP awarded the contract to a research team from Applied Research Associates, Incorporated (ARAI) in February 1998. ARAI consultants, in coordination with Arizona State University (ASU), worked on the project with the objective "to develop a guide that utilized existing mechanistic-based models and databases reflecting current state-of-the-art pavement design procedures". In June of 2004, the AASHTO joint task force on pavements published a first draft of the MEPDG (ARAI, 2004).

In 2005, Scott Wilson Pavement Engineering released its interim report after conducting an independent engineering review of the MEPDG for NCHRP Project 1-40A. Changes recommended were incorporated in MEPDG Version 0.8. In 2006, the final NCHRP Project 1-40A report was published and additional changes were adopted in Version 0.9 and 1.0 of the software. Although no additional changes have been made to the software, data updates are used to refine and upgrade the program models and reference database as needed.

2.7.2 Mechanistic-Empirical Pavement Design Guide

This design guide took state-of-the-art processes for every input to roadway design, whether mechanistic or empirical, and compiled a Windows based software that allows the user to change and input every aspect of the roadway design. Figure 2.7 shows the latest version of the MEPDG opening.

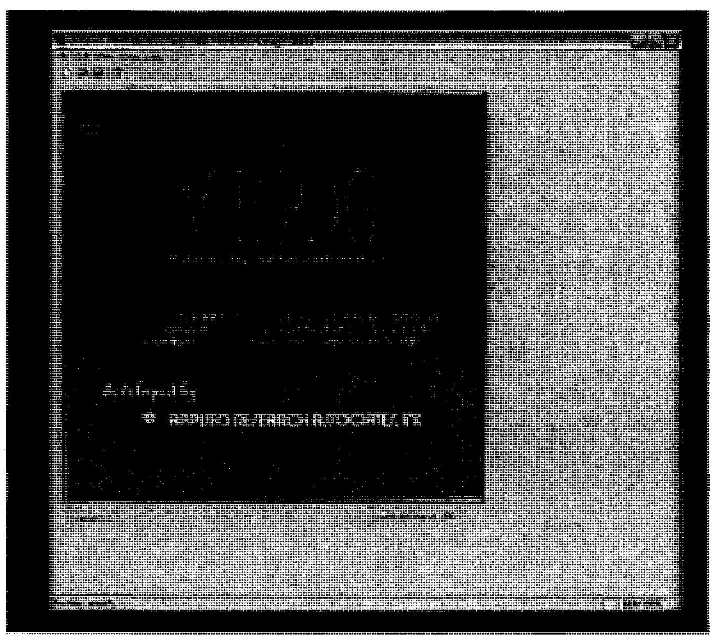


Figure 2.7: Current MEPDG Software

The design guide has been a work in progress. Although the theory behind the MEPDG is fully developed, the software to run the program is not. Each year since the initial publication there has been at least one software update to help solve some of these shortcomings. Currently there are still multiple software deficiencies in the program, particularly in the roadway foundation design. At the time of this research, the current MEPDG operates on software version 1.0 and with a "build update" of 24 May 2007.

2.7.2.1 MEPDG Model Input. The MEPDG model allows for multiple data entry points. Figure 2.8 shows the theoretical "roadmap" for the latest version of the MEPDG.

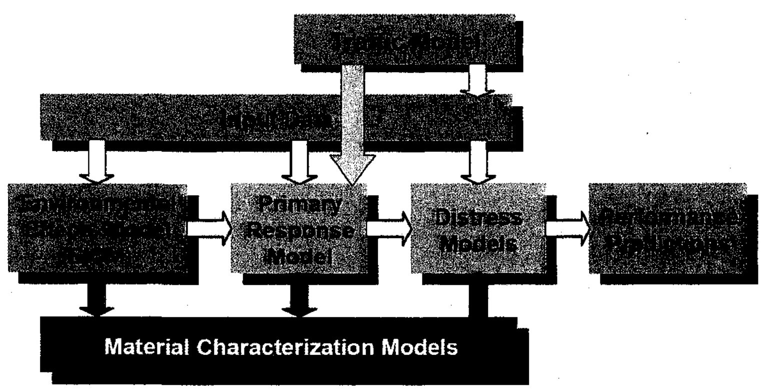


Figure 2.2.1. Interaction between materials module with other components of the M-E framework in the Design Guide.

Figure 2.8: MEPDG Theoretical Roadmap for Input and Analysis

Although a detailed discussion of every input data point is available at http://www.trb.org/mepdg/home.htm, the most important input, with regard to this research, is the material characterization models shown in green in Figure 2.8. These models allow the user to input the design properties for each layer based on data collected from the laboratory or the field. In addition, because the

MEPDG offers multiple models, the user has the ability to take current data on hand, regardless of test type, and still use the design guide. Again, a detailed discussion along with reason for the selection criteria is available as part of the MEPDG, but this research focuses on the roadway foundation design. The MEPDG breaks down the roadway structure by defining the wearing layer as Hot Mix Asphalt (HMA) and the roadway foundation as Layers 2 through 4. The MEPDG input screen for these layers is shown in Figure 2.9.

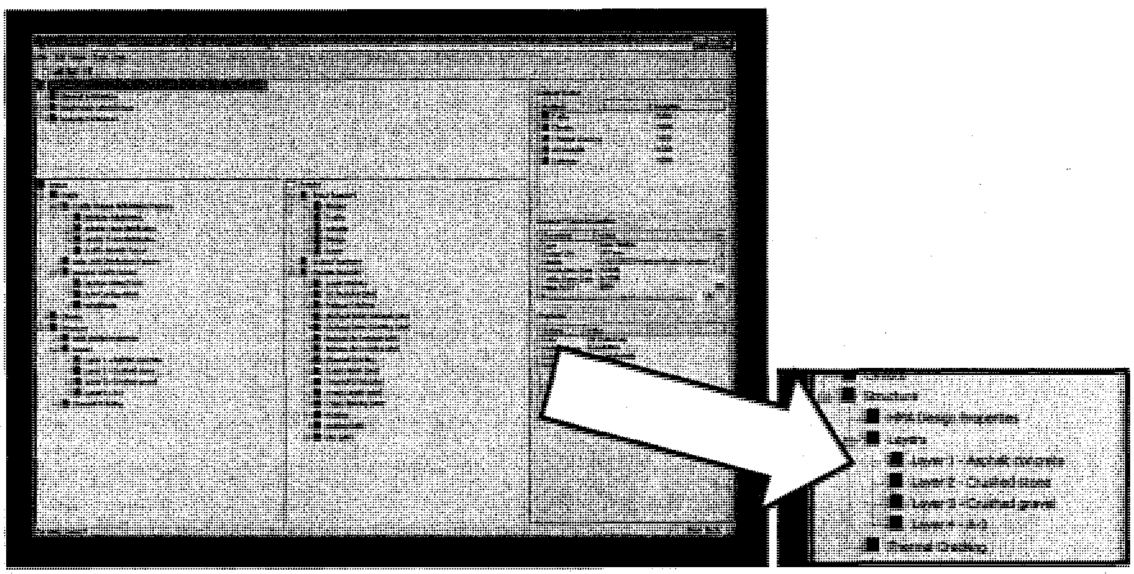
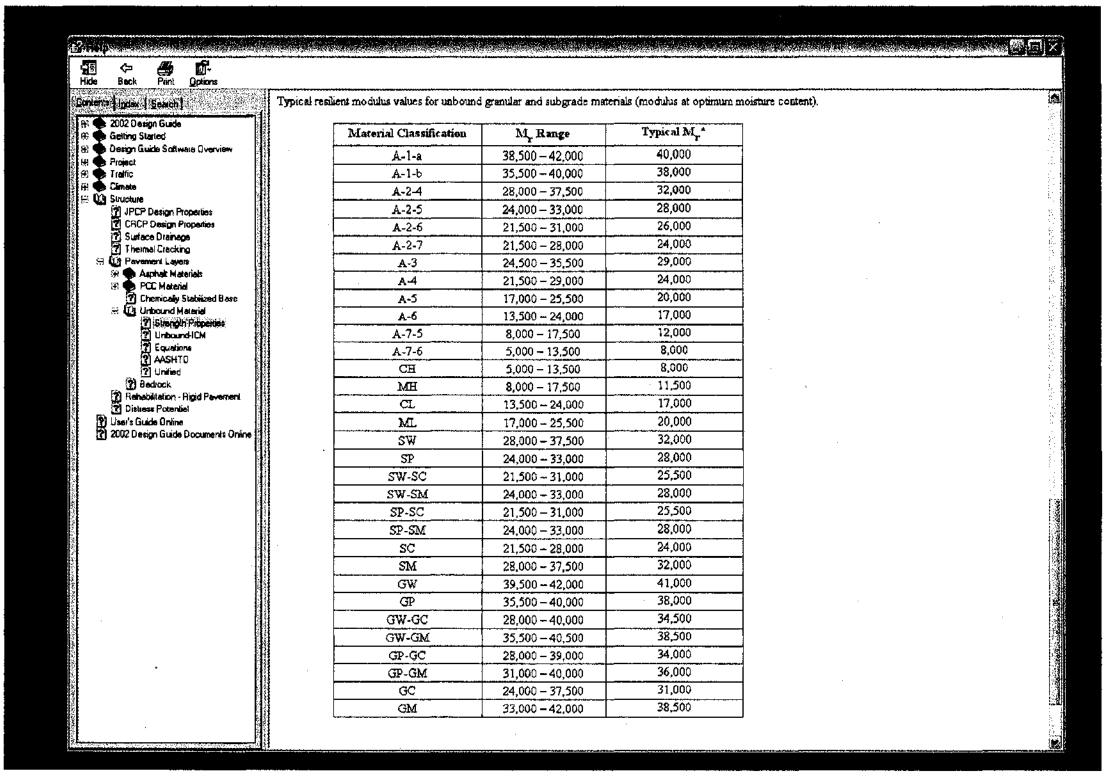


Figure 2.9: MEPDG Foundation Layer Input Screen

Using the MEPDG, layer-2 and layer-3 serve as the design input for base and subbase materials. In this case, the user is given three options for the design. The first option, the most generic input, is Level 3. Using Level 3 input, the user is required to determine the soil classification of their material using either the AASHTO classification or the Unified Soil Classification System

(USCS). The user is then directed to a table of national averages to select the corresponding M_R value based on their material at optimum water content. Figure 2.10 shows the MEPDG strength properties table to select the appropriate M_R value [psi], if this input method is selected.



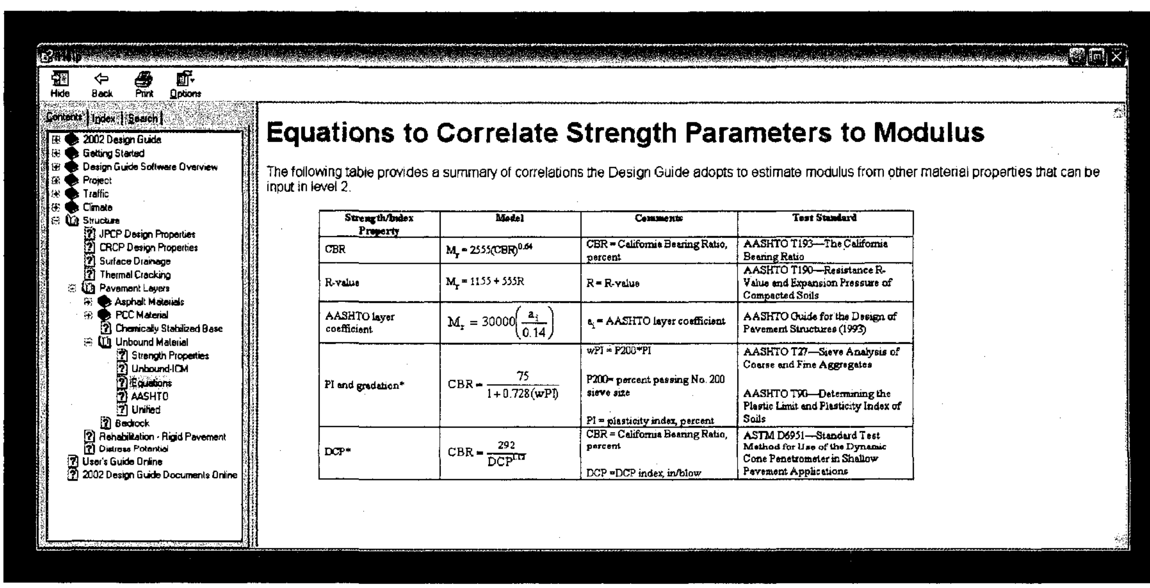
Typical resilient modulus values for unbound granular and subgrade materials (modulus at optimum moisture content).

Material Classification	M_r Range	Typical M_r*
A-1-a	38,500 – 42,000	40,000
A-1-b	35,500 – 40,000	38,000
A-2-4	28,000 – 37,500	32,000
A-2-5	24,000 – 33,000	28,000
A-2-6	21,500 – 31,000	26,000
A-2-7	21,500 – 28,000	24,000
A-3	24,500 – 35,500	29,000
A-4	21,500 – 29,000	24,000
A-5	17,000 – 25,500	20,000
A-6	13,500 – 24,000	17,000
A-7-5	8,000 – 17,500	12,000
A-7-6	5,000 – 13,500	8,000
CH	5,000 – 13,500	8,000
MH	8,000 – 17,500	11,500
CL	13,500 – 24,000	17,000
ML	17,000 – 25,500	20,000
SW	28,000 – 37,500	32,000
SP	24,000 – 33,000	28,000
SW-SC	21,500 – 31,000	25,500
SW-SM	24,000 – 33,000	28,000
SP-SC	21,500 – 31,000	25,500
SP-SM	24,000 – 33,000	28,000
SC	21,500 – 28,000	24,000
SM	28,000 – 37,500	32,000
GW	39,500 – 42,000	41,000
GP	35,500 – 40,000	38,000
GW-GC	28,000 – 40,000	34,500
GW-GM	35,500 – 40,500	38,500
GP-GC	28,000 – 39,000	34,000
GP-GM	31,000 – 40,000	36,000
GC	24,000 – 37,500	31,000
GM	33,000 – 42,000	38,500

Figure 2.10: MEPDG Level-3 Strength Property Chart

The second option, Level 2, allows the user to estimate the M_R value from a series of equations based on five soil indices. As shown in Figure 2.11, the user can estimate the M_R design value by CBR, R-Value, AASHTO Layer Coefficient, Plasticity Index and Gradation, or Dynamic Cone Penetrometer (DCP) index. It is important to note that if the DCP index is used, the user actually estimates the CBR value with the DCP index and then the CBR value is used to estimate M_R.

The third and final option uses the highest level of detail for the design process. This option does not use just one value for the M_R, but rather the entire test data set by using the K-values. As discussed in Section 2.6.6, the NCHRP selected the LTPP M_R modified universal equation model to represent this input level. Therefore, after conducting M_R testing in accordance with AASHTO T-307, the user must perform regression analysis using external statistical software to determine the K_1, K_2, and K_3 regression coefficients. If the regression of the modified model results have R^2 values greater than 0.90, the Level-1 option may be used. However, if the R^2 values are less than 0.90, the MEPDG suggests using the Level-2 option with the test data actual average M_R rather than modeling the M_R response.



Equations to Correlate Strength Parameters to Modulus

The following table provides a summary of correlations the Design Guide adopts to estimate modulus from other material properties that can be input in level 2.

Strength/Index Property	Model	Comments	Test Standard
CBR	$M_r = 2555(CBR)^{0.64}$	CBR = California Bearing Ratio, percent	AASHTO T193—The California Bearing Ratio
R-value	$M_r = 1155 + 555R$	R = R-value	AASHTO T190—Resistance R-Value and Expansion Pressure of Compacted Soils
AASHTO layer coefficient	$M_r = 30000\left(\frac{a_i}{0.14}\right)$	a_i = AASHTO layer coefficient	AASHTO Guide for the Design of Pavement Structures (1993)
PI and gradation*	$CBR = \frac{75}{1+0.728(wPI)}$	wPI = P200*PI P200= percent passing No. 200 sieve size PI = plasticity index, percent	AASHTO T27—Sieve Analysis of Coarse and Fine Aggregates AASHTO T90—Determining the Plastic Limit and Plasticity Index of Soils
DCP*	$CBR = \frac{292}{DCP^{1.12}}$	CBR = California Bearing Ratio, percent DCP =DCP index, in/blow	ASTM D6951—Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications

Figure 2.11: MEPDG Level-2 M_R Correlation Equations

Provided regression results meet the guidance, the MEPDG offers two additional options at this point, to model the change in M_R throughout the year due to climatic effects of material property changes due to temperature. Either the user can enter the K-values for each month of the year to reflect the changes or they can enter the average K-values and allow the MEPDG to calculate the estimated change in K-values based on climatic data and soil gradation.

2.7.2.2 MEPDG Output. Once all input design is complete, the user runs the analysis to determine the final model performance over the design life span. The design guide gives a user many output files from the analysis to include surface down damage, bottom up cracking, thermal cracking, transverse cracking, rutting, and total distress. The design guide distress summary categorizes all cracking and rutting in one large output Excel file. This summary allows the user, in one file, to determine long-term performance of the analyzed roadway. The maximum distress of the road is reported annually in the Excel output file. Consequently, the long-term distress at the end of the evaluated period is reported in inches. This provides a convenient method to compare multiple analyses.

2.8 Summary

With unlimited potential, recycled concrete has a valuable place in reusable construction material. Finding the right use, both economically and environmentally, might not be has hard as once thought. However, regardless of the type of material used in roadway design, the first step is quality testing to determine the material and strength properties. Although M_R may prove harder than other tests, there are still useful products from such a test. Using those results, along with others, in the pavement design guide is where engineering judgment and careful consideration produce a proposed roadway design.

CHAPTER 3

MATERIALS & METHODS

3.1 Introduction

This chapter discusses the materials and methods used in the laboratory to characterize samples and analyze testing results. The materials include multiple gravelly and sandy non-cohesive samples from both New Hampshire and Maine. The methods include physical characterization of samples, bearing ratio testing, resilient modulus testing, and design performance modeling of the materials.

3.2 Materials

The material selected for this project consisted of both successful highway performance road foundation material and recycled construction by-product materials being considered for roadway use. The materials used for this research were donated by the Maine Department of Transportation (Maine DOT) and the Environmental Resource Return Corporation (ERRCO) in Epping, New Hampshire. In total, there were 12 samples, nine from Maine, and three from New Hampshire.

Maine samples consisted of seven road base materials selected by the Highway Testing Division as high-performance natural material currently in use statewide and two recycled samples of blended gravel and construction by-products scheduled for use in future Maine DOT projects. The seven samples of natural material donated were collected from various pits around the state to characterize statewide variability in materials. All samples were collected from the respective quarries by Maine DOT laboratory technicians. When collected the material was placed into five sandbags, each bag with 0.75 cubic feet of material and weighing approximately 70 pounds. The bags were then transported to the Maine DOT testing facility in Freeport, Maine and stored inside their testing building. The 45 bags were picked up in Freeport, Maine, transported to the UNH campus in Durham, New Hampshire, and stored in Kingsbury Hall until testing started. After inspecting each sandbag, the contents were found to have very similar gradations. However, as a precaution to ensure quality samples, two bags were blended together prior to research testing.

New Hampshire samples consisted of three recycled construction by-products being considered for roadway base construction in New Hampshire. Although the C&D debris originates in various locations around New Hampshire, all material was processed, refined, and blended in Epping, New Hampshire. ERRCO took the raw, unsorted C&D debris, and removed concrete from the stream. Then after stockpiling for approximately one year, the material was crushed, blended, and available for resale as coarse-grained aggregate material. The New Hampshire samples were collected from the actual stockpile at the ERRCO facility in Epping, New Hampshire. As with all mechanically created stockpiles, there is some natural segregation. Consequently, separate samples were taken throughout the stockpile at three different heights and later remixed. The 22 samples were placed into five gallon buckets, weighing 50-pounds each, at the site and transported back to the UNH campus at Durham, New Hampshire. Once at UNH, the samples were stored in Kingsbury Hall until testing. Prior to testing, three buckets were mixed together, one from each location in the stockpile, to create a homogenous sample.

In summary, all 12 materials are coarse-grained (4"-) with suitable quantities available for base/subbase construction. Table 3.1 lists summary data for all 12 samples while Figure 3.1 shows samples taken (2"-) from each of the 12 materials prior to testing.

[illegible]	Original Data/Information			
	Owner	Location	Type	Max Size
ME-1	Rocky Hill Quarry	Eliot, ME	Gravel	2"-
ME-2	Gracelawn	Auburn, ME	Gravel	4"-
ME-3	Pike Industries	Augusta, ME	Gravel	2"-
ME-4	Pike Industries	Wells, ME	Sand & Gravel	1.5"-
ME-5	Pike Industries	Sidney, ME	Gravel	2"-
ME-6	Shaw Brothers	Gorham, ME	Sand & Gravel	4"-
ME-7	Shaw Brothers	Dayton, ME	Sand & Gravel	4"-
	Shaw Brothers	Dayton, ME	C&D: RAP, RCA, Gravel	4"-
	Shaw Brothers	Gorham, ME	C&D: RAP, RCA, Brick, Gravel	4"-
	ERRCO	Epping, NH	C&D: RCA, Brick, Wood	2"-
	ERRCO	Epping, NH	C&D: RCA	2"-
	ERRCO	Epping, NH	C&D: RCA, Brick	2"-

	Natural Materials
	Recycled Materials

Table 3.1: Materials Data Summary Table

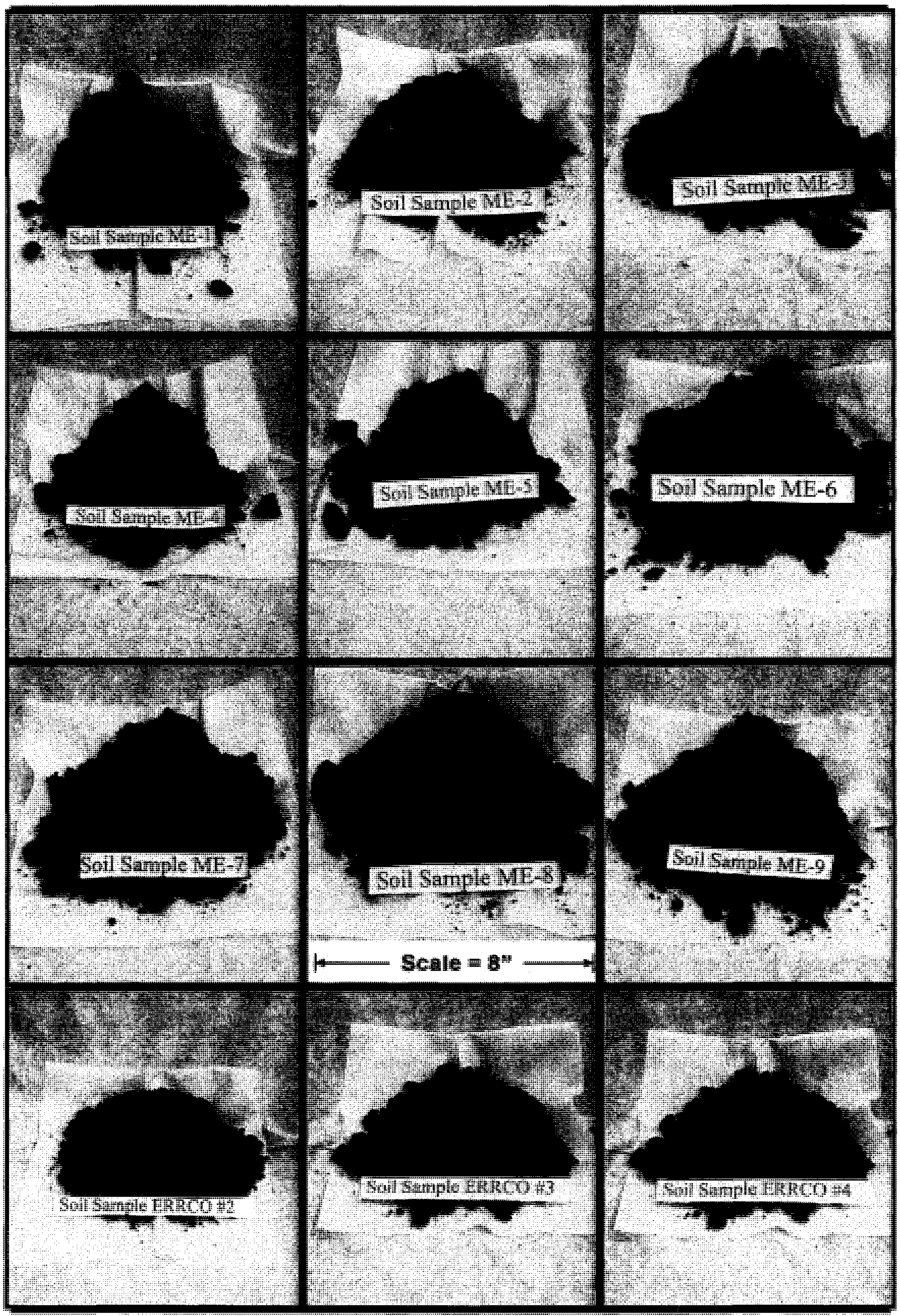


Figure 3.1: Material Samples Prior to Testing (Scale Applies to Each Sample)

In an effort to evaluate the effects of different components in the C&D debris by-product stream, ERRCO-2 was tested in original condition from the stockpile. ERRCO-3 and ERRCO-4, however, were modified before testing. As listed in Table 3.1, the primary components of ERRCO-2 were RCA, Brick, and random wood particles. To analyze the effect of the wood particles, ERRCO-4 was tested with the wood particles hand removed; leaving RCA and brick. To further determine the effect of brick, ERRCO-3 was tested with brick and wood hand removed. Although close attention was given to removing the particles in question, minute amounts of wood or brick were still present.

3.3 Methods

These materials were being considered for roadway construction and therefore all testing procedures followed AASHTO standards. A systematical procedure break down for each laboratory test is available in all annual AASHTO Standard Specifications for Transportation Material and Methods of Sampling and Testing 22nd Edition or later. AASHTO Edition 22 was used for this research.

3.3.1 Material Classification

All samples were classified using the same procedure and standards. All materials donated arrived at the lab in either 70-pound sandbags or 50-pound buckets. To ensure representative samples, two or three specimens were combined, blended, and mixed to ensure a homogenous material. Following blending, each sample's grain size distribution was determined through sieve analysis. The samples were sieved through U.S. Standard Sieves in sizes 4.0, 2.5, 2.0, 1.5, 1.0, 0.75, 0.50, 0.375 inch and #4, #8, #16, #30, #50, #100, #200. After sieving, the Uniformity Coefficient (C_U) and Coefficient of Curvature (C_C) were calculated and used to determine the Unified Soil Classification. Table 3.2 shows the task and method for this laboratory process.

Task	Method	Remarks
Grain Size Distribution	AASHTO T-88	Sieve Analysis (Dry)
Unified Soil Classification-1	Uniformity Coefficient	$C_U = \frac{D_{60}}{D_{10}}$
Unified Soil Classification-2	Coefficient of Curvature	$C_C = \frac{(D_{30})^2}{(D_{60} * D_{10})}$

Table 3.2: Material Classification Procedure

3.3.2 Material Attributes

Upon completion of classification, sub-samples of each material were removed for specific gravity, Atterberg limits, and Loss On Ignition (LOI) testing. These three tests were used to help further classify the tested materials for comparison purposes and possibly allow other researchers to compare the results with other similar materials. The Atterberg limits define the liquid limit and plastic limit of the sample and allow calculation of the plasticity index, if applicable. The LOI testing was conducted at 550°C as required by standards for organic and bituminous samples. Because the samples from New Hampshire did not have recycled asphalt, the LOI determined only the organic materials present. Similarly, the Maine samples contained recycled asphalt but did not have organics such as wood. Therefore, the LOI determined the amount of asphalt binder present. Table 3.3 shows the corresponding AASHTO test used for each material attribute.

Task	Method	Remarks
Specific Gravity	AASHTO T-100	Volumetric Flask (Vacuum)
Liquid Limit	AASHTO T-89	Atterberg Limit-1
Plastic Limit	AASHTO T-90	Atterberg Limit-2
Organic/Bituminous Content	AASHTO T-267	Loss On Ignition

Table 3.3: Material Attribute Procedure

3.3.3 Optimum Water Content and Maximum Dry Density

After classification, the moisture-density relationships were evaluated for each sample. This procedure is better known as the Proctor test and is used to determine the optimum water content and maximum dry density. There are four method options for AASHTO procedure T-180. Method C was selected because this procedure uses a 4-inch Proctor mold with 10-pound hammer and most closely represents the M_R testing procedure as it also uses a 4-inch specimen with 10-pound hammer. In addition, Method 3 most closely represents the CBR testing procedure by using the same size compaction hammer. Figure 3.2 shows the Proctor test underway for sample ERRCO-2.

The results of this procedure are extremely important, as both the CBR and M_R are sensitive to water content. Therefore, by AASHTO standards, these tests must be conducted at the optimum water content, ±1%, and at maximum dry density, ±3%. As a result, the following procedure served as the guidelines for research. AASHTO procedure T-180 was conducted two or three times for each sample to confirm the results with the following strategy. Because the accuracy of AASHTO procedure T-180 is ±1% water content, the first two tests were performed and averaged. If the deviation was less than 2% water content, the average value was reported as the optimum water content.

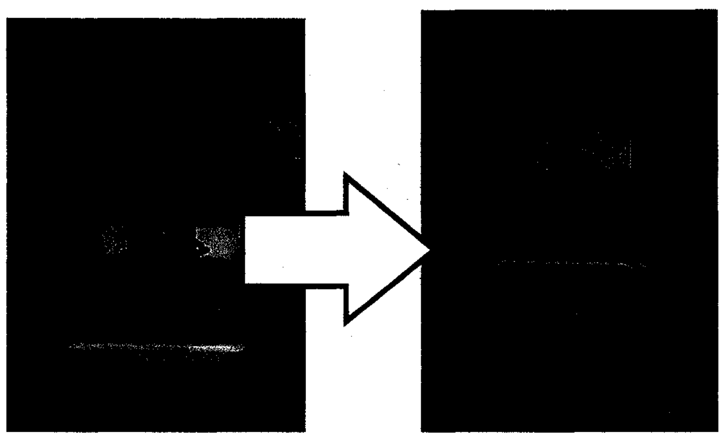


Figure 3.2: Proctor Testing (Compaction and Trimming) on Sample ERRCO-3

If the testing failed to meet the first criteria, a third test was conducted as a confirmation. If the optimum water content of the confirmation test was ±1% of the averaged optimum water content than the averaged value of all three tests was reported as the optimum water content. It is important to note this optional third test was not actually required as the first two tests for all samples were within 2% water content for each of the 12 samples. Chapter 4 covers these results in detail.

As required by AASHTO T-180, the water content of each Proctor sample was calculated by averaging two samples from each specimen. AASHTO procedure T-265, laboratory determination of moisture content of soils, was used to determine the water content. Table 3.4 shows the corresponding AASHTO tests used for the Proctor testing.

Task	Method	[illegible]
Maximum Dry Density	AASHTO T-180	Method C
Optimum Water Content	AASHTO T-180	AASHTO T-265

Table 3.4: Dry Density and Water Content Procedure

3.3.4 Vibratory Hammer Calibration

Testing standards for M_R allow for three types of compaction while preparing the soil specimen: 10-lb Proctor hammer, vibratory hammer, or kneading compactor. The vibratory hammer was selected for ease of use and compaction uniformity. To ensure that the in-house vibratory hammer (Bosch Model 11263) produced compaction results similar to the proctor hammer, a series of time tests were conducted to calibrate vibration time and dry density. This testing was completed in standard protector molds with both a proctor hammer and the vibratory hammer. Once the correct vibration duration was determined, the same compaction time was used in the M_R 4-inch mold.

3.3.5 Bearing Ratio

As discussed in Chapter 2, the CBR is the standard for determining and evaluating the bearing strength of soil samples. Where:

$$CBR = \frac{\sigma_1 (at\Delta_V = 0.1''Corrected)}{1000[psi]} \qquad \text{(Equation 2.1)}$$

$CBR =$ California Bearing Ratio [%]

$\sigma_1 =$ Principal Stress (vertical) [psi]

$\Delta_V =$ Vertical Deformation [inches]

The CBR procedure has two water content options. The first and most common option is conducting the bearing ratio at optimal water content. Because the test is sensitive to material water content, this ensures that test results from different samples may be compared without correction factors. This option of the CBR is the equivalent of evaluating the optimum strength for the soil. However, the procedure can also be conducted for a range of water contents. This option would allow a user to estimate the bearing ratio in field conditions that are other than optimal. For this research, the optimal water content option was selected to compare the 12 materials because it removes the variability of strength due to water content in each of the samples. In addition, the M_R is conducted at optimum water content and allows a direct comparison by standard conversion equations.

The CBR procedure also allows for unsoaked or soaked tests. For the same reasons stated above, the soaked version of the bearing ratio was selected because CBR to M_R conversion equations are based on soaked CBR values. Figure 3.3 shows the CBR test conducted on Sample ME-6. The first frame shows the CBR load frame being setup. The second frame shows the sample during loading. The final frame is the ME-6 sample upon completion of testing.

Figure 3.3: California Bearing Ratio Test on Sample ME-6

AASHTO standards caution that past practice has shown the CBR results, for those materials having substantial percentages of particles retained on the #4 sieve, are more variable than for finer materials. Consequently, more trials may be required for those materials to establish a reliable CBR (AASHTO, 2002). Since the base/subbase materials used for this research testing fell into this category, the following strategy served as the guidelines for testing.

Using the same methodology described for the Proctor test, a reliable CBR value was determined by conducting two or three CBR tests for each sample. The first two tests were conducted and averaged together and the deviation calculated. If the deviation was greater than 20%, a third test was conducted. If the third test, compared to the average of the first two tests, was less than 20% deviation, then the combined average of all three CBR tests served as the final value. If the third test fell outside of 20% deviation, than additional tests were conducted, outliers determined and removed, and the average calculated as the final average CBR. Again, it is important to note that a third test was not required in any of the research testing and Chapter 4 covers the testing results in detail.

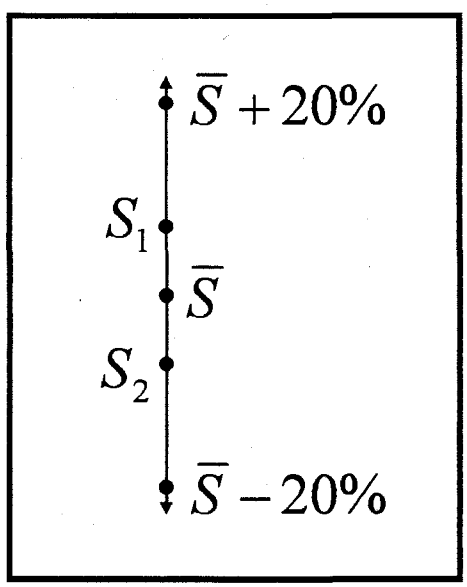


Figure 3.4: Testing Methodology Example

Figure 3.4 shows this methodology graphically where: the first sample CBR is S_1, the second sample CBR is S_2, and the average CBR is $\bar{S}$. In this example, S_1 and S_2 are numerically between $\bar{S} \pm 20\%$ and therefore did not require a third test. Conversely, if S_1 and S_2 fell outside $\bar{S} \pm 20\%$, then a third, and possibly additional, CBR test would be required.

The CBR testing was completed on UNH's bearing ratio load frame and data collected by a GCTS computerized data acquisition system. The load frame has a 10,000-pound capacity and analog system for determining penetration rates. The penetration rates were confirmed prior to testing and recorded for each specimen. The system used a 10,000-pound load cell between the load frame and CBR plunger to collect stress data. The system used a Macro-Sensor Lateral Variable Displacement Transducer (LVDT) mounted on the CBR plunger and displacement transducer tip placed on the CBR mold to collect penetration data. The GCTS system collected the stress and strain data at 0.1-second intervals during the test. The collected data was then used to create the required AASHTO stress-strain curve. Although not required by AASHTO for the CBR test, a strain-time curve was also generated to confirm the penetration rates met procedural guidelines for each test. Specimens were prepared at optimum water content ±1%, and then compacted to maximum dry density ±3%.

3.3.6 Resilient Modulus

As discussed in Chapter 2, the M_R represents a simulation of the physical conditions and stress states of materials beneath flexible pavement subject to moving wheel loads. The modulus testing sequence is divided into two categories based on materials: subgrade and base/subbase. The same base/subbase sequence was used for all 12 samples. AASHTO test T-307 procedures allow for specimen diameters of 71, 100, and 152 millimeters. All testing was performed on 100-mm (4-inch) specimens as the in-house M_R system was calibrated for that size.

Using the same methodology for optimum water content and CBR, two or three tests were conducted for each sample. The first two tests were conducted and then the average modulus was calculated for each test (15 cycles of information per test). This value served as the proposed M_R for that specimen. If the deviation of the tests were less than ±20% of the average then the M_R was recorded as the M_R. However, if the deviation was greater than ±20%, then a third, confirmation test, was conducted to confirm the data. If the third test average resilient modulus was within 20% deviation of the proposed value than the average, of all three tests, served as the reported M_R. Refer to Figure 3.4 for the graphical testing methodology. Similar to Proctor and CBR testing, this third test was not required and further analysis is provided in Chapter 4.

Figure 3.5 shows the M_R test for sample ERRCO-4. The first frame shows the load frame with a sample after start-up procedures have been completed. The second frame shows the sample prior to starting the testing. The final frame shows a sample after 16 cycles of testing and upon completion of the optional quick shear test as the specimen is forced to shear failure (σ_3 = 34.5 kPa).

All testing was completed on UNH's in-house GCTS triaxial testing load frame and GCTS data acquisition system. The GCTS system uses a computer controlled servo valve to regulate hydraulic pressure for the load frame piston. The system uses a second computer controlled servo valve to regulate the air confining pressure in the specimen chamber. Both the load frame piston pressure and air confining pressure vary throughout the tests' 16 cycles as per AASHTO test T-307. The GCTS load frame capacity is rated for 50,000-pounds.

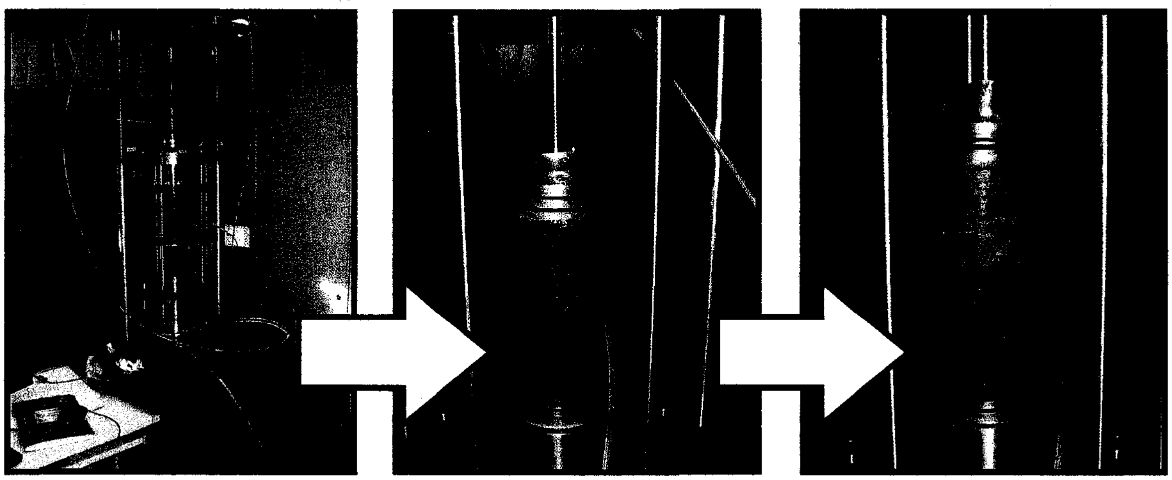


Figure 3.5: Resilient Modulus Test on Sample ERRCO-4 and ME-2

The system uses a 10,000-pound load cell between the load frame piston and triaxial chamber. It also uses two Macro Sensor LVDTs mounted on the chamber load rod with the spring displacement transducers tips on the top of the triaxial chamber. In addition, the system uses an Omega pressure cell transducer to record the triaxial chamber confining pressure. Data from the load cell, LVDTs, and pressure cell are collected by the GCTS data acquisition system. This data is collected every 0.5 seconds during non-loading sequence and every 0.01 seconds during loading sequence. Components of the M_R apparatus used for testing are shown with labels in Figure 3.6.

$$\overline{M}_R = \frac{\sigma_{dh}}{\varepsilon_R} \qquad \text{(Equation 2.3)}$$

The collected data allows the user to calculate deviator stress and resilient strain, which is then used to calculate the resilient modulus per Equation 2.3. Specimens were prepared at optimum water content ±1%, and then compacted to maximum dry density ±3% as required by testing standards.

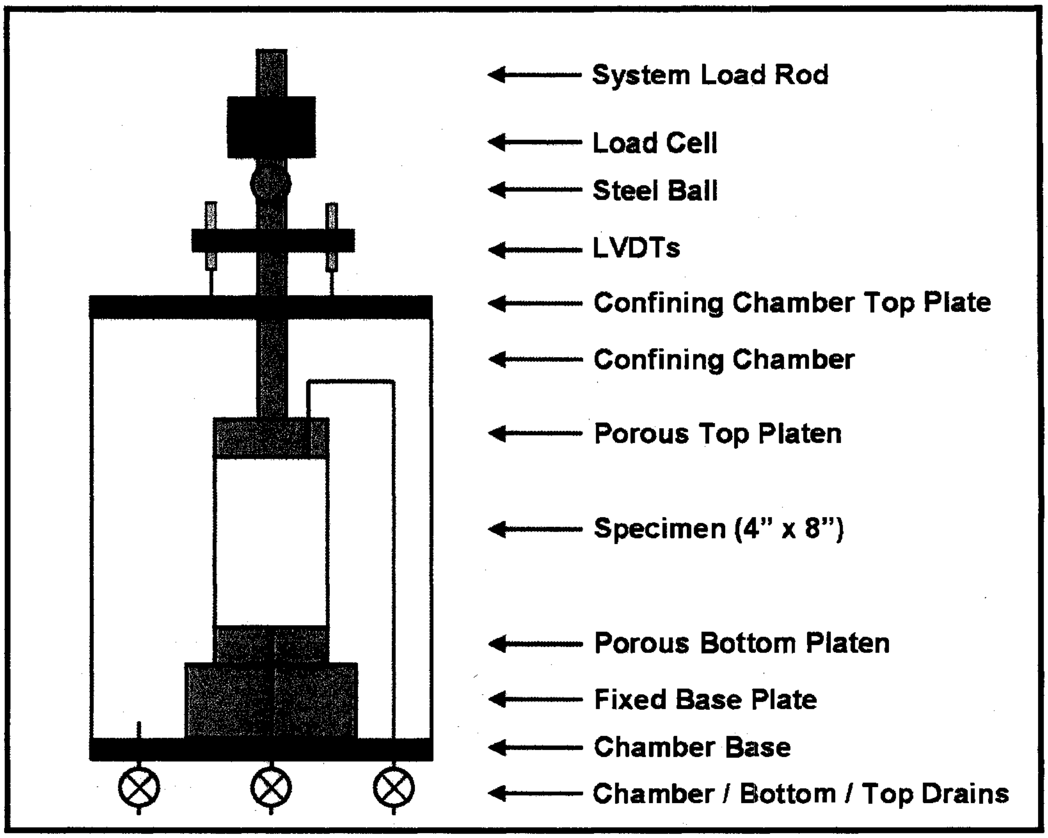


Figure 3.6: Resilient Modulus Testing Apparatus

3.3.7 Increasing Resilient Modulus Repeatability

As discussed in Chapter 2, a vast amount of research has been dedicated to help researcher's achieve repeatable results with M_R testing. To this end, there were numerous recommendations identified in Chapter 2 that were taken into account during this research. The following paragraphs describe the laboratory actions based on M_R literature.

The M_R testing is extremely sensitive to startup procedures and specimen stresses. Because of these concerns, a number of trial tests were conducted prior to research testing. Based on recommendations from the literature review, during this time a rigorous startup procedure checklist was established to ensure repeatable results over the course of testing. This startup procedure complied with AASHTO T-307 test procedure but added additional verification steps to ensure correct specimen preparation. In addition, this startup procedure locked out certain servos during preparation to ensure the GCTS system did not apply erroneous stresses on the specimens. Using the additional startup procedures, membranes of the same thickness, and similar brand membranes helped ensure reliable results. A sample of the M_R startup procedure checklist is located in Appendix A. These steps were added based on the research from Groeger et al. in 2003.

Another recommendation from the literature involved Peak-Intensity-Duration (PID) controls. The PID controls are a very important software tool that allows the user to control the load pulse and prevent erroneous specimen stresses during testing. Normally, the applied load is fine-tuned with PID control at the beginning of testing only. However, LTPP ETG Team Leader, Aramis Lopez, concluded after detailed M_R studies that monitoring and adjusting the PID throughout testing was required to ensure the peak load applied matched that of AASHTO standards for all sequences. (Groeger et al., 2003) Consequently, during this research, PID controls were adjusted during the entire testing program.

Figure 3.7 is a screen capture of the GCTS system during M_R testing. On the screen, the PID controls are visible. The bottom of the screen shows the AASHTO required load in blue and the actual applied load in black. As visible in Figure 3.7, the applied load matches the required load almost flawlessly. Chapter 4 discusses the results found from PID adjustment during pre-testing experiments.

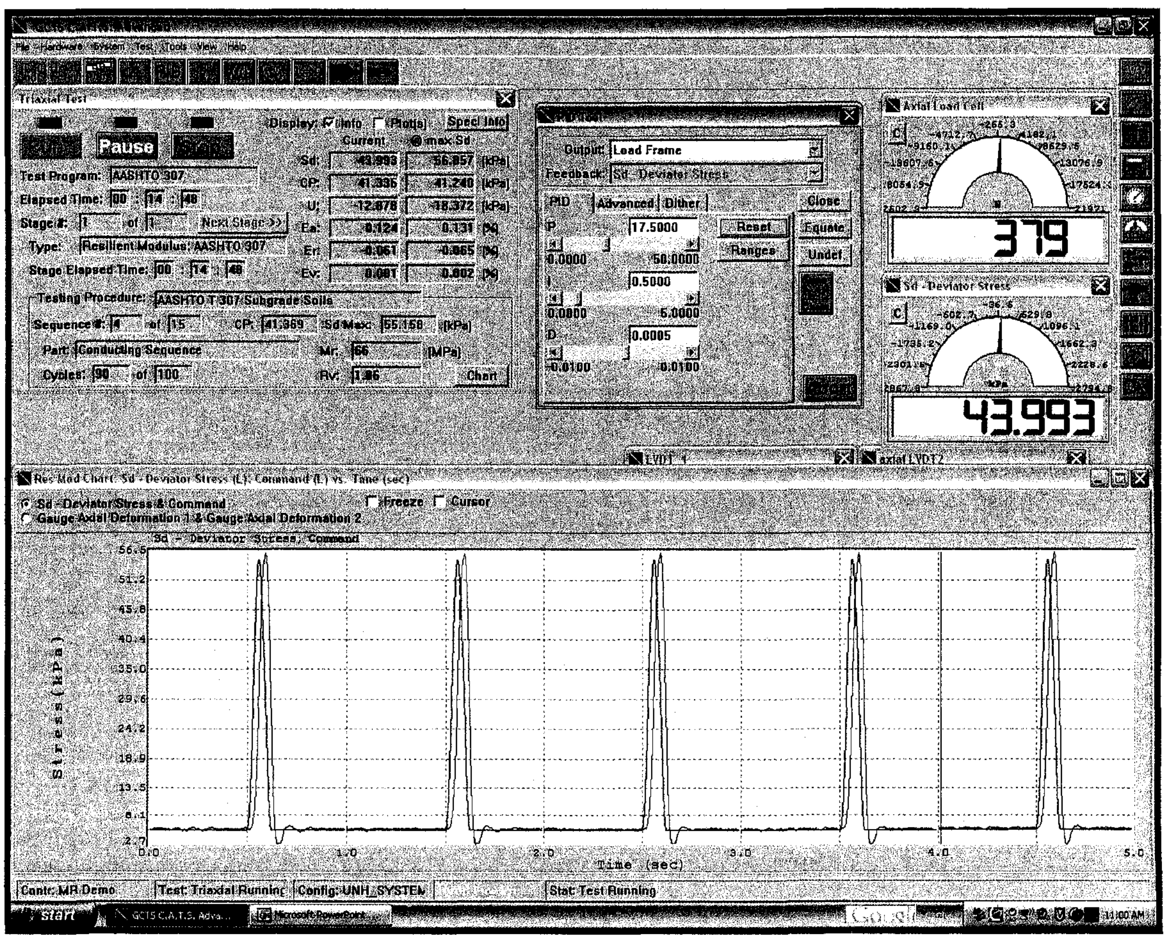


Figure 3.7: Resilient Modulus Test Control Screen with PID Tool

In addition to the PID recommendation of monitoring to ensure peak load applied match that of AASHTO standards by the LTPP M_R Team Leader, this research took the following laboratory actions to ensure repeatable M_R results (Groeger et al., 2003).

1) Load Pulse Reasonableness→ Monitored PID settings throughout testing.

2) Deformation Response Reasonableness→ Changed LVDTs twice (finally ending with spring loaded) to confirm proper LVDT data collection.

3) Confining Pressure Conformity→ Switched from water to air confinement after repeated system failures due to water cylinder.

4) Sample Integrity→ GCTS installed option to stop and confirm testing at 5% strain. This option allowed identification when a sample failed, i.e. no longer considered an elastic response.

5) Post Processing→ Confirmation and independent calculation of bulk stress, deviatoric stress, and M_R then checked the recommended values and response as per LTPP. This resulted in nine tests being identified and rerun.

Based on the findings from the 1998 round robin proficiency testing about individual specimen variation (Section 2.6.4), all M_R research was conducted with multiple replicated specimens for each material. Using multiple specimens of the same material and following the testing methodology previous mentioned, allowed for the averaging of M_R values to overcome the high variability inherent with M_R (Boudreau, 2003).

Applying the research findings from Boudreau Engineering regarding compaction methodology, hydraulic servo problems, LVDT placement, and system calibration, this research took many precautions to overcome the trouble areas (Boudreau, 2003). As previous discussed in M_R methods, vibratory hammer calibration timing was completed to ensure specimen compaction matched the maximum dry density ±3%. Hydraulic servos were locked out prior to testing to prevent erroneous stresses applied. To overcome LVDT problems, three different LVDTs were evaluated prior to testing to ensure proper size and style. The final LVDT selected, after numerous trial runs, was a spring loaded Macro Sensor with 0.5-inch capacity. Conducting the trial runs for LVDT selection ended up being very important because the LVDTs that arrived with the GCTS system had numerous failures and problems during testing. The final testing procedure taken, based on Boudreau's findings, was the extensive load cell and LVDT calibration described in M_R testing setup (Boudreau, 2003). As previously mentioned, this daily recalibration prevented nine M_R tests with erroneous data from being reported. Chapter 4 discusses these results.

3.3.8 Statistical Analysis

The statistical software used for all statistical analysis was DataFit Version 8.2. This software suite allowed for detailed analysis of existing models. In addition, data fit results were confirmed with JMP 7.0 statistical software. Although this software does not easily analyze existing models, it does provide graphical representation of the statistical results, which is useful for interpreting model fit. The first model analyzed statistically was the modified M_R equation as shown in Equation 2.7. Regression was performed to determine the K_1, K_2, and

K_3 variables and the R^2 value calculated. After determining the K-values, predicted M_R were calculated and compared to actual M_R values and the R^2 value for the fit determined.

$$M_R = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\tau_{OCT}}{P_a}\right]^{K_3} = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sqrt{2}}{3}\frac{\sigma_d}{P_a}\right]^{K_3} \quad \text{(Equation 2.7)}$$

The second model analyzed statistically was the CBR to M_R predictive model as shown in Equation 2.8. Results from using the equation to predict M_R were compared to actual M_R values and the R^2 value for the fit calculated.

$$M_R = 2555(CBR)^{0.64} \quad \text{(Equation 2.8)}$$

The K-values, M_R predictive values, and statistic fit data for both models are presented in Chapter 4.

3.3.9 Simulation of Material Performance

The MEPDG was used to evaluate the performance of each material. The design guide requires input for traffic, axial load distributions, climate, hot mix asphalt, asphalt concrete, base/subbase, and subgrade.

To ensure accurate comparison for New England conditions, a base model was used to provide accurate information for New Hampshire's traffic patterns, axial load patterns, hot mix asphalt, and asphalt concrete. Dr. Jo Sias Daniel provided this MEPDG base model from the Civil Engineering Department at UNH. The base model provided actual measured data from a section of I-393 in Chichester, NH as part of her research on Hot Mix Asphalt (HMA) and Recycled Asphalt Pavement (RAP). This input base model file, in conjunction with NCHRP climatic data for Rochester, New Hampshire, insured the MEPDG results were applicable to the New England region. The only variable in the pavement design guide for this research was the base/subbase layer. Holding all other MEPDG options constant allowed for isolation of base/subbase effects on the roadway-simulated performance.

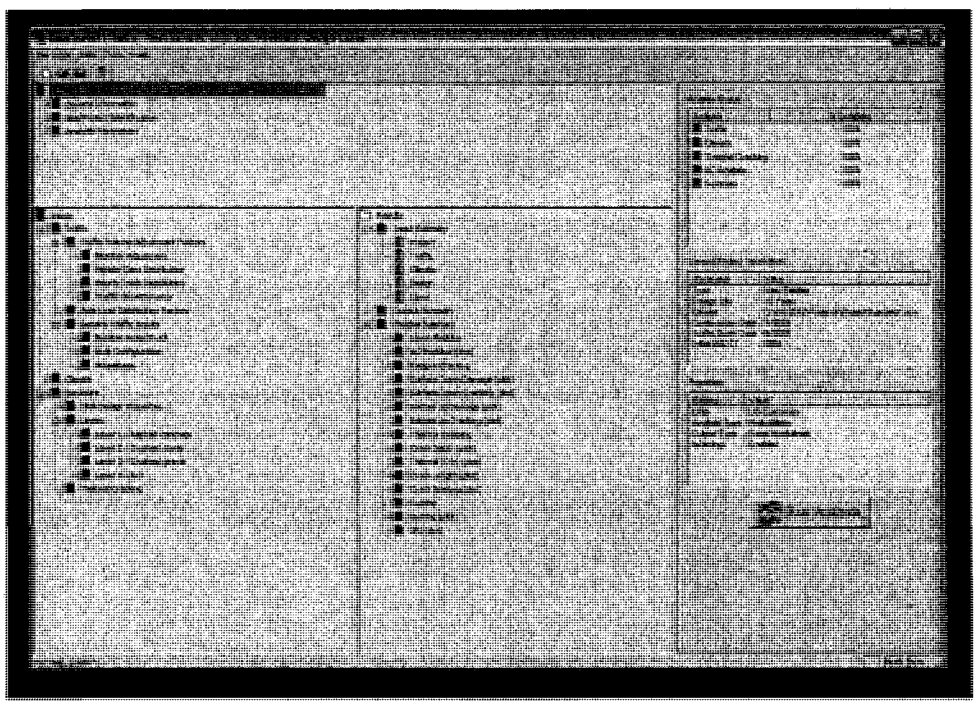


Figure 3.8: MEPDG Base Model for Simulations

Figure 3.8 shows the MEPDG loaded with the "Base Model (Thesis)" file that served as the same start point for all simulations. The MEPDG uses a red or green box to indicate complete data sets were properly loaded. The green boxes in Figure 3.8 also indicate the base model is valid and ready to operate. Confirmation of the base model was an important step to assess all base model assumptions and verify data entry prior to the simulation.

Once the base model was established, the road deflection extremes were modeled using the design guides' minimum and maximum CBR values and minimum and maximum M_R. After these minimum and maximum brackets were established, the design guide was rerun with each specimen's specific average CBR and average M_R to determine comparative performance with Level-2 data. Finally, each sample's K-values were to be used to determine comparative design guide performance with Level-1 data. However, the simulation methodology was changed, as the current MEPDG (Version 1.0 with 24 May 2007 Update) cannot calculate the final road analysis using any K-values. At the time of this research, Level-1 input for the design guide is still not functional. Figure 3.9 shows the error message that the Finite Element Model (FEM) is not calibrated for use with the MEPDG at this time. Therefore, it was not possible to compare the M_R K-values for each sample.

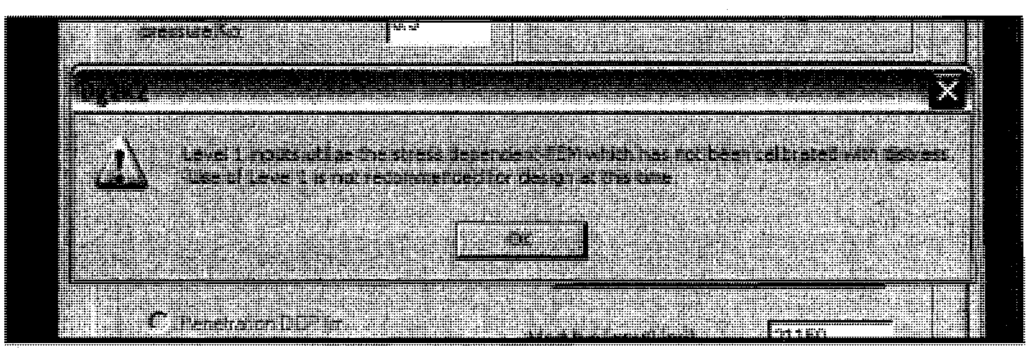


Figure 3.9: MEPDG Error Message for Level 1 Input

Regardless of input type, the MEPDG output summary shows each type of distress both in table form and graphically. Figure 3.10 shows an example of the graphic rutting output. All forms of rutting are presented as well as the NCHRP rutting cutoff. The MEPDG uses the M_R to determine long-term behavior by estimating plastic behavior from the elastic response during testing. Therefore, the best way to analyze the performance of the road is total distress and rutting. For this research, the total rutting was recorded at year 10 and reported as the samples rutting value.

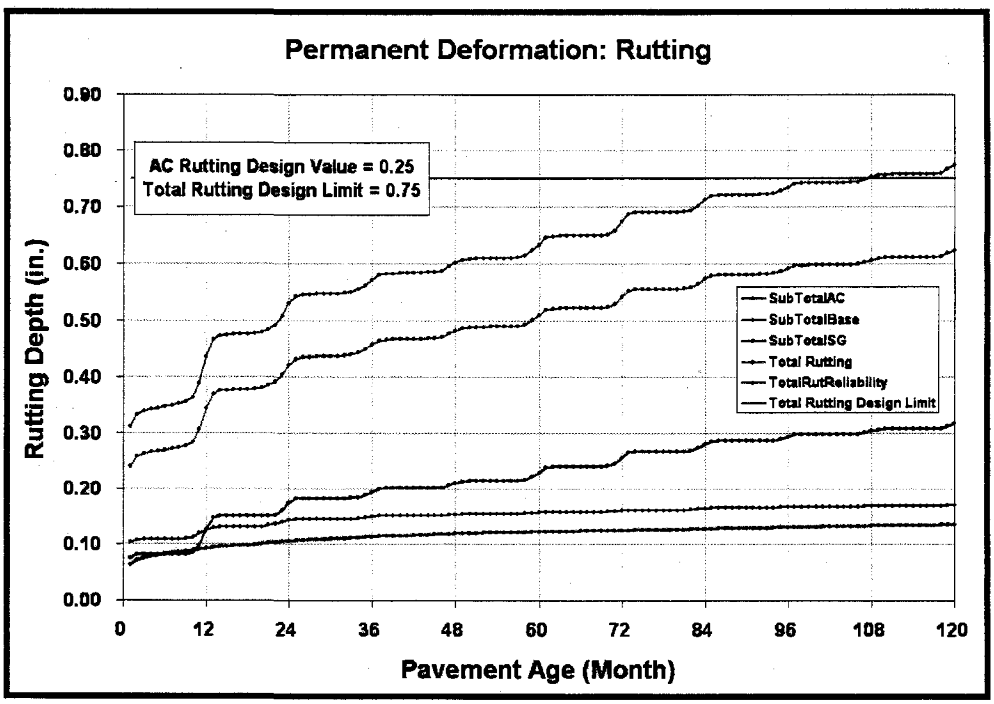


Figure 3.10: Graphic MEPDG Rutting Output File (10 Year)

3.3.10 Laboratory Conditions

All laboratory testing was conducted in Kingsbury Hall on the campus of UNH in Durham, New Hampshire between February and September of 2007. All soil classification testing was conducted in laboratory room S126 and S125 while all CBR and M_R testing was conducted in laboratory room S124. Both laboratory rooms are environmentally controlled with a temperature ranging from 65° to 72° and average humidity of 45%. A La Crosse Technology Indoor/Outdoor weather station was used to monitor conditions throughout testing.

3.3.11 Quality Control and Quality Assurance

To ensure reliable results during testing, a sample material with known material properties was subjected to the complete battery of testing from soil classification to resilient modulus. Using this sample material allowed for the confirmation of procedural checklists and ensured proper setup, startup procedures, and execution for all tests. After creation and confirmation of the checklists, LVDT calibration and load cell calibration was conducted on both CBR equipment and M_R testing equipment. Upon completion of calibration, a quality control set of tests were conducted with the sample material. The results were then compared to the known material properties of the soil confirming the test procedures.

To ensure reliable CBR results, the CBR load cell and LVDT gains and voltage offsets were confirmed before every test. Prior to starting testing each week, the CBR load cell was recalibrated with a 10K load ring and CBR LVDT was confirmed with a digital caliper. To ensure reliable M_R results, the M_R load cell and LVDT gains and voltage offsets were confirmed prior to every test. In addition, the M_R load cell was recalibrated with a 10K load ring and the M_R

LVDTs were confirmed with a digital caliper prior to testing each week. At numerous points throughout testing, when a computer error occurred or erroneous M_R values were calculated, the load cell and LVDT readings were reconfirmed and if need be recalibrated. Over the 4 month testing period, this stringent procedure prevented nine tests with flawed data from being recorded and the tests repeated.

3.3.12 Summary

Since M_R testing is a new testing protocol, there is an enormous amount of literature dedicated to reviewing the test standards and recommending laboratory procedures to achieve repeatable results. A vast amount of time was devoted to ensure all known pitfalls were overcome before research testing began. Additionally, AASHTO procedures were used as the standard-bearer for all research from material classification to strength testing to ensure this research met DOT requirements.

CHAPTER 4

RESULTS & DISCUSSION

4.1 Introduction

Chapter 4 presents the results from this research and discusses the application of the CBR predictive model, effectiveness of the M_R modified equation model, and simulated long-term performance by the MEPDG. Where applicable, comparisons are made and analyzed to help further understand the effects of M_R testing. Charts, graphs, and tables are used to summarize the results, while the complete laboratory results for most tests and empirical analysis results for each comparison are presented in the Appendices.

4.2 Material Classification

4.2.1 Grain Size Distribution

Grain size distribution was performed on all 12 samples via sieve analysis according to AASHTO procedure T-88. The laboratory data for the sieve analysis can be found in Appendix B. The samples were all coarse-grained materials and very similar in composition. The 50% finer diameter ranged from 0.6 to 0.04 inches (#16 sieve). Demonstrating how similar the materials are, nine of the samples only varied in 50% finer from 0.2-inches to 0.1-inches. Figure 4.1 shows the grain size distribution for all materials.

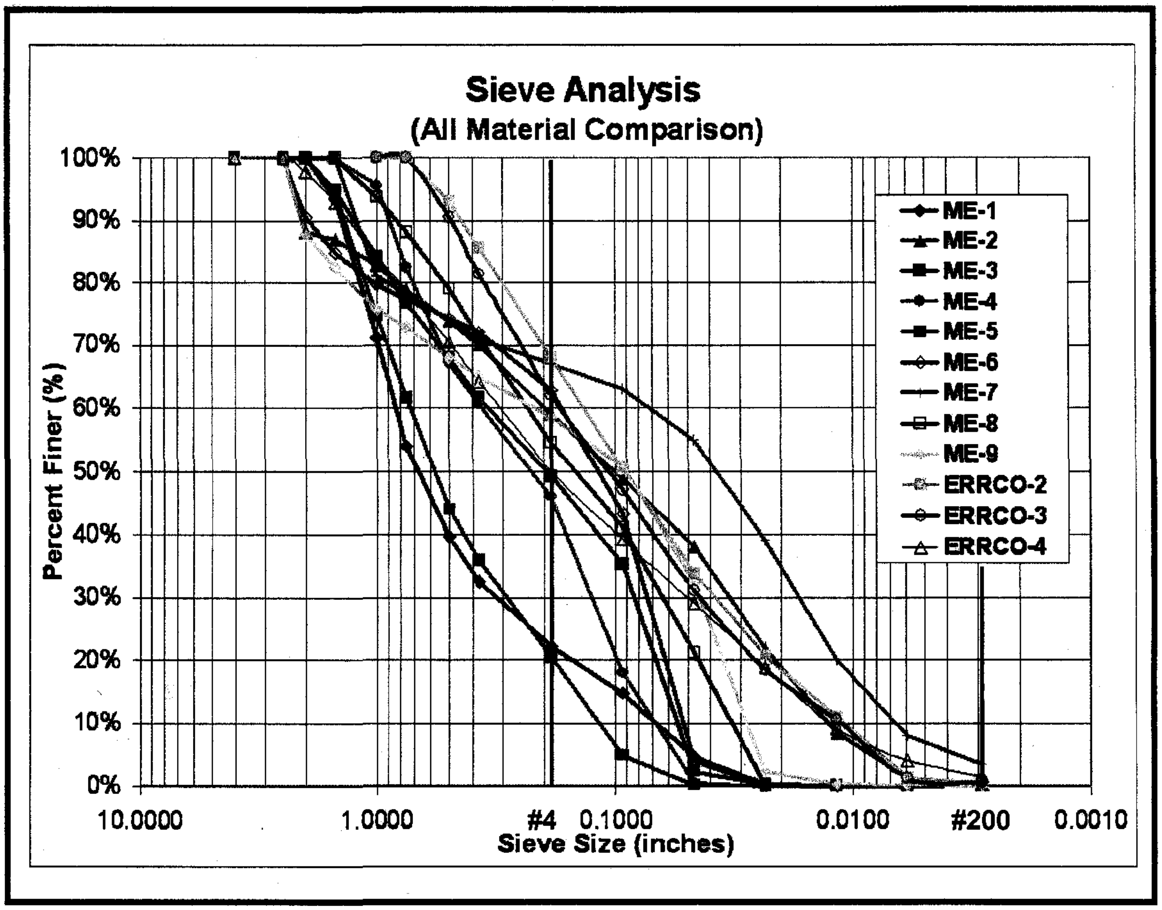


Figure 4.1: Grain Size Distribution for all Samples

Samples ME-1, ME-2, ME-3, ME-4, ME-5, ME-6, and ME-7 were natural material currently in use by the Maine DOT as base/subbase fill. These samples served as a baseline with which to compare all recycled materials due to long-term successful performance in Maine roadways. Samples ME-8 and ME-9 were blends of C&D debris (concrete and asphalt) with gravel. These samples are currently under consideration for use in roadway base/subbase application by contractors for the DOT. ME-7 served as the gravel base for ME-8 with 30% added C&D debris, while ME-6 was the base gravel for ME-9 with 30% C&D debris blended. Samples ERRCO-2, ERRCO-3, ERRCO-4 were 100% concrete

C&D debris crushed and blended from New Hampshire. The three ERRCO samples originated from the same stockpile but were further refined for the purposes of this research to help determine the effects of different components in the samples. However, the material gradation for samples ERRCO-3 and ERRCO-4 were maintained as close to ERRCO-2 as possible to eliminate variations in material strength due to grain size. Figure 4.2 shows the grain size distribution for the three ERRCO samples.

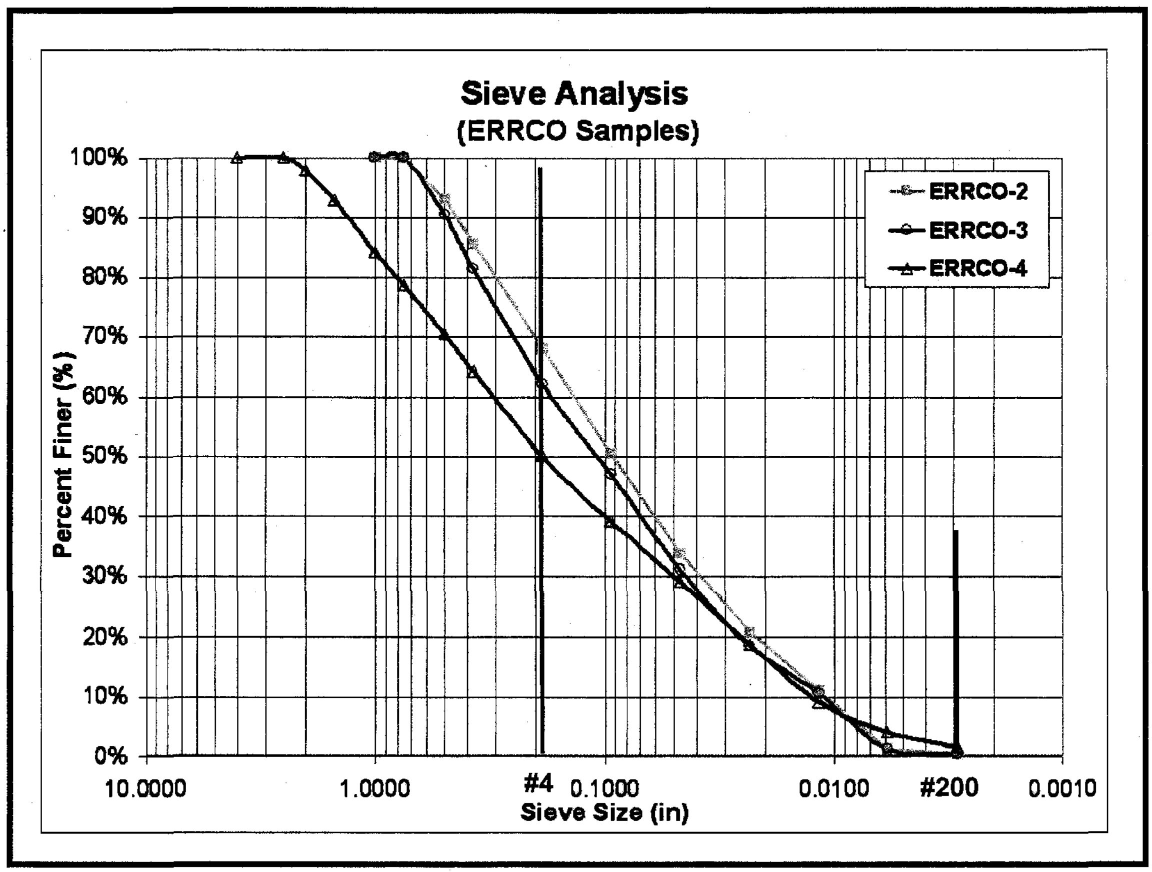


Figure 4.2: Grain Size Distribution for all ERRCO Samples

As discussed in Section 3.2, in an effort to evaluate the effects of different components in the C&D debris by-product stream, ERRCO-3 and ERRCO-4 had wood and brick hand removed respectively. The brick removed from ERRCO-4 was approximately 12% of the sample by weight while the wood removed from ERRCO-3 was approximately 2% of the sample by weight.

4.2.2 Unified Soil Classification System

Using the Unified Soil Classification System (USCS), all materials were categorized through grain size distribution. The gradation of each sample was determined using the Uniformity Coefficient (C_U) and Coefficient of Curvature (C_C). All 12 materials were categorized as gravel/sand in nature. While ME-1 was categorized as well graded gravel, all other gravels were categorized as poorly graded. ERRCO-2 and -3 were well graded sand, other sands were poorly graded. Table 4.1 shows the Uniformity Coefficient (C_U), Coefficient of Curvature (C_C), and USCS group symbol for each sample.

[illegible]	[illegible]	[illegible]	[illegible]
ME-1	12.09	2.35	[illegible]
ME-2	15.71	0.56	[illegible]
ME-3	7.50	0.47	[illegible]
ME-4	6.00	0.96	[illegible]
ME-5	6.00	0.96	[illegible]
ME-6	7.99	0.97	[illegible]
ME-7	15.62	0.40	[illegible]
[illegible]	10.00	0.77	[illegible]
[illegible]	7.19	0.45	[illegible]
[illegible]	12.00	1.34	SW
[illegible]	15.98	1.01	SW
[illegible]	32.05	0.50	SP

Table 4.1: Unified Soil Classification Data

The classification for the recycled materials is important because it allows direct correlation to similar baseline materials (ME-2 through ME-7) for CBR and M_R. In addition, Figure 4.1 shows that despite some samples being graded as sand and others as gravel, all samples were very similar in nature, grain size, and gradations. The grain size data collected is presented in Appendix B.

4.3 Material Attributes

4.3.1 Specific Gravity

AASHTO test T-100 was used to determine the specific gravity for each of the 12 samples. A volumetric flask and vacuum were used over the period of 24 hours to achieve requirements of the pycnometer as per AASHTO procedure. After testing a calibration failure was identified in the scale used for specific gravity testing. As specific gravity was only calculated to better classify the material and not used as part of the research, the calculated values are not reported due to the possible error. However, the common specific gravity range for the type of material tested is reported in Table 4.2 (Das, 1997).

[illegible]	[illegible]	[illegible]	G_s
Sand	104	135	2.16
Sand w/ Gravel	108	145	2.32
Gravel w/ Sand	120	137	2.20
Gravel	105	125	2.00
Concrete Crushed	135	150	2.40

Table 4.2: Common Specific Gravities

4.3.2 Atterberg Limits

All materials were gravel/sand and non-cohesive in nature and therefore had very little fines. Consequently, they do not exhibit a plastic limit nor have a Plasticity Index. Despite no plastic limit, laboratory time was dedicated to determining the liquid limit with AASHTO test T-89 to better define each material for comparison by other agencies. However, the liquid limit was not possible due to grain size (percent passing #200 sieve ≤5%). All samples are therefore categorized as non-plastic.

4.3.3 Loss On Ignition

The LOI technique was used to determine the organic content of ERRCO-2, ERRCO-3, and ERRCO-4 and the bituminous content of ME-8 and ME-9. AASHTO test T-267 established the first stage LOI temperature at 110°C for water content followed by a user selected ceiling temperature based on the material being ignited. Industry standard for organic material is a 500°C ceiling temperature while standard bituminous ceiling temperature is 550°C.

[illegible]	[illegible]
[redacted]	3.91
[redacted]	1.04
[redacted]	4.15
[redacted]	2.19
[redacted]	2.90

Table 4.3: Loss on Ignition (Bitum or Organic %) for Recycled Samples

An important note with the bituminous LOI is that the aggregate components of the recycled material are not lost during ignition. Therefore, the weight lost is only the binder content of the recycled material. However, the loss still helps to clarify the composition of the C&D blends from Maine. Table 4.3 is a summary of the LOI for recycled materials.

4.4 Optimum Water Content and Maximum Dry Density

The purpose of AASHTO test T-180 is to determine the optimum water content of a soil. However, part of the procedure used to determine the optimum water content is to determine the wet density and then calculate the maximum dry density. Both aspects of this test are vital to producing accurate results during CBR and M_R testing because they are sensitive to variations in water content. Therefore, ensuring that all strength testing is performed at optimum water content prevents erroneous variations in the data that are interpolated as material strength effects. Similarly, producing samples that are not at maximum dry density is interpolated as plastic material behavior and generates false lower strength. Both water content and density variations can lead to results with high inconsistency and therefore decrease repeatability. Using the methodology described in Chapter 3 ensured an accurate optimum water content and maximum dry density. The results shown in Table 4.4 are the average results of the two proctor tests. Because no deviation exceeded 20%, two tests accurately defined both the optimum water content and maximum dry density.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ME-1	7.00	1.41%	135.50	3.32%
ME-2	7.25	3.45%	133.90	1.19%
ME-3	6.00	0.83%	140.65	3.31%
ME-4	6.75	3.70%	139.63	0.63%
ME-5	6.50	5.88%	142.25	3.69%
ME-6	8.50	4.19%	131.50	0.38%
ME-7	8.75	2.86%	129.48	0.60%
	7.50	1.64%	131.08	0.25%
	10.00	5.94%	127.33	0.33%
	16.75	1.49%	108.25	2.54%
	16.50	0.00%	110.75	0.23%
	16.50	0.00%	111.70	0.63%

Table 4.4: Optimum Water Content and Maximum Dry Density for all Samples

The natural samples varied in optimum water content from 6.0% to 8.75%. This is a very small band and consistent with the expected range for this type of non-cohesive granular material. However, the recycled materials have much higher contents. Due to the presence of wood, brick, and crushed concrete, these samples have a much higher capacity for water. In addition, these components have a much higher porosity than the soil fines and therefore must be near saturation before the water content allows the sample to compact in a denser configuration. ME-8 was the one exception. This recycled sample contained mostly recycled asphalt pavement as the C&D debris. Its binder, coating all the C&D aggregate, prevented the absorption of extra water.

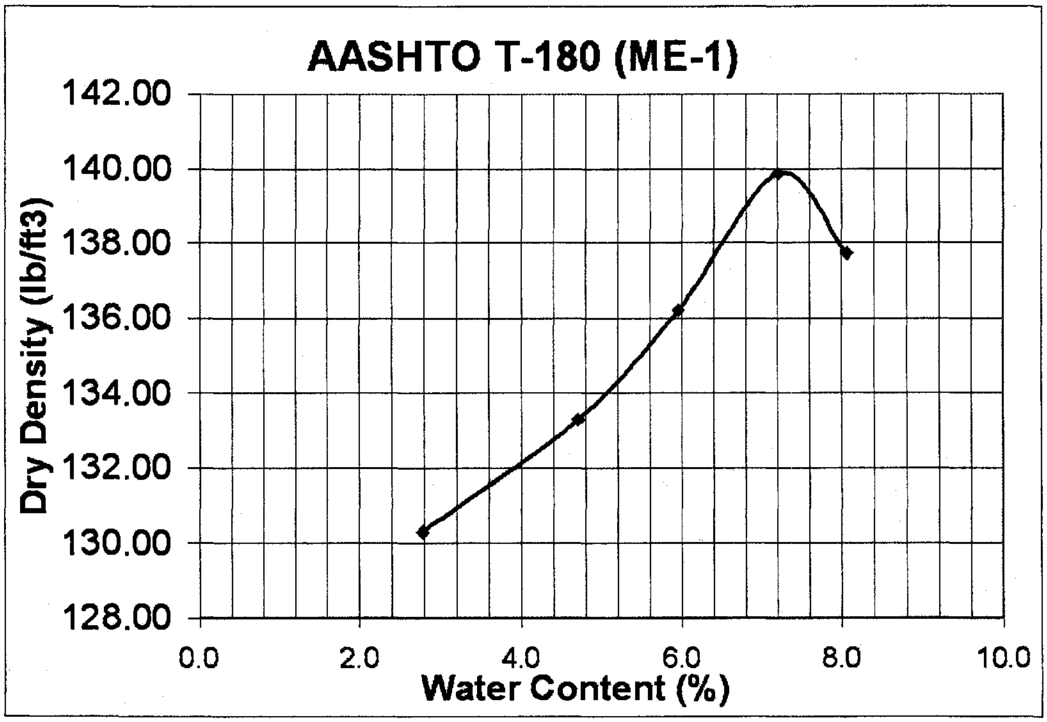


Figure 4.3: Sample AASHTO T-180 Graph (ME-1)

Although the maximum dry densities of the samples varied from 108 lbs/ft^3 to 142 lbs/ft^3, it was expected that the three ERRCO samples would have a significantly lower maximum dry density due to the presence of wood and brick in the samples. Figure 4.3 provides a sample of water content versus dry density used to determine the optimum water content and is representative of the data collected for all 12 samples. All densities were in the expected range and provided important target densities for later compaction in 4-inch M_R molds. All data collected and density plots generated as part of AASHTO test T-180 are available in Appendix C.

4.5 Bearing Ratio

As previously mentioned, CBR values were the standard-bearer for all strength testing of base, subbase, and subgrade materials for many years. Many DOTs have CBR records dating back for decades. Although not very effective for selecting material for high traffic roadways, the CBR is a permanent part of the DOT culture. Depending on location, subgrade material may range from a CBR of 15% to 50%, while base/subbase is greater than 50%. However, the individual CBR values over 100% are rarely considered important in the design industry. Simply put, when used in the base/subbase design application, a material is either 100% or not. If below 100%, the material value is used. Conversely, a material that is 125% is not engineered differently than a material with 100%. This inconsistent use of the CBR is seen throughout the industry to include the MEPDG. Even though the CBR was designed for subgrade use and later expanded to base/subbase applications, the scale still stops at 100% for design purposes. However, CBR testing still reports the actual number after normalizing even when greater than 100% and there is certainly a difference in the material strength of a sample with 100% versus a material with 200%. When operating with base/subbase materials, it is common to find CBR values that range from 100% to 300%.

4.5.1 CBR Testing Results

Table 4.5 lists the CBR testing results for each sample, the average CBR value, and the deviation. Thorough startup procedures and meticulous system calibration produced highly repeatable testing results. None of the 12 samples produced deviation greater than 12.1% (ERRCO-4) which was well below the 20% criteria established in Chapter 3 for testing methodology.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ME-1	**353.00**	**317.30**	**335**	**5.33%**
ME-2	**108.15**	**120.83**	**114**	**5.54%**
ME-3	**312.50**	**300.23**	**306**	**2.00%**
ME-4	**257.87**	**257.34**	**258**	**0.10%**
ME-5	**124.30**	**103.03**	**114**	**9.35%**
ME-6	**99.00**	**93.91**	**96**	**2.64%**
ME-7	**79.82**	**76.26**	**78**	**2.28%**
	54.20	**48.85**	**52**	**5.19%**
	91.30	**91.10**	**91**	**0.11%**
	38.65	**43.14**	**41**	**5.49%**
	70.64	**69.80**	**70**	**0.59%**
	50.06	**63.77**	**57**	**12.05%**

Table 4.5: CBR Testing Results for all Samples

As expected, the Maine samples currently in use are all high quality materials that meet the industry standard (75%) for base/subbase application. Results ranged from 78% (ME-7) to 335% (ME-1). When test results for ME-1 and ME-3 showed CBR values over 300%, the Maine DOT material testing center was contacted for more information about the fill. Mr. Wade McClay, head of the testing center, confirmed the materials were the state's best performing fills and generated from gravel pits with high quality sand/gravel deposits. All CBR data is presented in Appendix D.

4.5.2 C&D Debris Effects on CBR

Both of the Maine recycled samples, ME-8 and ME-9, were blends of existing gravel samples with 30% C&D debris added. For example, ME-9 was a blend of gravel from the same pit (Gorham, ME) as ME-6 and blended with local C&D debris. Whereas ME-8 was a blend of gravel from the same pit (Dayton, ME) as ME-7 and blended with local C&D debris. Therefore, it is possible to investigate the effect of 30% C&D debris on both ME-8 and ME-9.

ME-6 produced an average CBR value of 96%. While ME-9, the same gravel blended with RAP and RCA, produced an average CBR of 91%. With a historical variability of 12% deviation, it is not possible to determine if the C&D debris caused the slight reduction of 5% or if the change was simply statistical variation. Testing raw samples of the C&D debris used to create ME-9 would provide details, but samples were not available to test.

ME-7 produced an average CBR value of 78%. Blending this virgin material with local C&D debris composed of RAP, RCA, and brick produced the recycled blend ME-8 and a CBR value of 52%. Similar to ME-9, ME-8 was approximately 30% C&D debris, but this blend resulted in a CBR reduction of 40%. Well above the 12% deviation seen in CBR testing, it is easy to conclude the C&D debris caused the reduction.

What is not known from this testing, is if the relationship between 100% gravel and 100% C&D debris is linear. If it was a linear relationship, then blending easily could achieve the desired material properties based on the construction requirements. This could save vast amounts of money for natural materials replacement and testing. Only two set of tests would be required, one for raw C&D debris and one for raw virgin aggregate. However, if the change were not linear then a series of tests would be required to determine the approximate strengths of each blend percentage before using the recycled materials. Unfortunately, the C&D debris materials used for ME-8 and ME-9 were not from the same source and varied in content, which prevents analyzing if the same C&D debris affects varying aggregates differently. It also prevents analysis on the effect of brick in the C&D debris. However, the ERRCO samples should provide this data.

The ERRCO samples were of the same base material, consisting of crushed recycled concrete from the C&D debris stream. While ERRCO-2 was a sample that included the ubiquitous wood and brick, ERRCO-4 had the wood removed, and ERRCO-3 had both wood and brick removed. Intuitively, the removal of wood and brick should increase the material compressive strength (F_C) because the F_C of wood and brick are much lower than that of concrete ($F_C \geq$ 3-ksi). However, this might not be the case and must be considered carefully.

While ERRCO-2 produced an average CBR value of 41%, ERRCO-3 and ERRCO-4 produced average values of 70% and 57% respectively; therefore, the removal of wood, 2% by weight, lead to a 32% increase in CBR. This increase exceeds the 12% CBR deviation and is statistically important. For the same reason, the removal of wood and brick, 2% and 12% respectively, lead to a 52% increase in CBR. However, the 10% change in ERRCO-3 values and ERRCO-4 values, prevent statistical confirmation to analyze the removal of brick alone. The variation due to brick can be estimated from ERRCO-2, -3, and -4 at 10% to 20% ± 12%.

4.6 Resilient Modulus

The M_R test was designed to more accurately model a soil column under vehicular traffic than the CBR test. Like most tests or models that are more accurate in their methods, it is also much more complicated. Despite nationwide problems with repeatability of M_R testing, the objectives of this research demanded repeatable results in order to draw conclusions about the effects of C&D debris on the M_R. This lofty goal proved much harder to set in motion than originally considered.

Unlike the CBR testing apparatus, two or three trials runs does not make one proficient in the use of the system. Every variable component of the triaxial testing equipment has long-term second and third order effects on the sample. It takes some considerable rehearsal time just to understand these interactions. Consequently, in January of 2007, M_R pre-testing started on samples that were not part of the research data. The material used for this practice was similar in composition and gradation to the ERRCO samples. However, after 12 M_R tests, and not a single pair of data that could be repeatable, it was time to bring in outside help. In February and again in April 2007, GCTS consultant Peter Goguen conducted training on the system, upgraded the software, and recalibrated the hydraulic servo valves feedback process. Once completed, tests conducted on rubber test blanks produced results within the GCTS design standards. Following the training and system upgrades, some 25 additional training tests were completed while LVDTs were evaluated. As discussed in Chapter 2 and 3, two of the most important steps to ensure accurate M_R results are thorough startup procedures and PID tuning. The training tests focused on ensuring both skills sets were ready for the research testing.

4.6.1 Confinement Fluid

Although AASHTO standard calls for confinement by air only, research for Protocol 46 determined confining fluid had no impact on the M_R results and NCHRP standards allow for either air or water. When pre-research testing began, the GCTS M_R was set up to run with air confinement as per AASHTO standards. However, after numerous problems with maintaining confining pressures, GCTS technicians recommended switching to water confinement and adopting the ASTM standards. In February of 2007, when GCTS representative Peter Goguen visited to help with training, he converted the system for water confinement. Despite initial success, the confinement problems actually increased after the upgrade. In April 2007, Mr. Goguen returned, upgraded the software, recalibrated the system, switched the confinement back to air, and ran confirmation tests. Once the upgrade was complete, and problem equipment replaced, there were no additional problems with confinement fluid. All research testing was completed using this updated software and air as the confining fluid.

4.6.2 Startup Procedures

The purpose of the startup procedures are to guarantee that erroneous stresses are not applied to the sample prior to testing. Because the triaxial system is capable of applying large hydraulic piston loads, it is very easy to apply large undesired deviatoric stresses to the sample. In addition to using the 25 training tests to learn the system and select LVDTs, these tests served to refine startup procedures.

The principal goal of the startup procedure was to prevent undesired stresses on the sample. The first step to achieving this goal was to reconfirm load cell, LVDT, and air sensor gain and offsets. This step ensured the proper profile was loaded in the testing system and that the desired stress, via load cell feed back, was applied once the load rod made contact with the upper platen. Once gain and offsets confirmed the load cell, LVDT, and air sensor were configured properly, they were rezeroed to ensure proper starting levels. The second step was to disable all computer-controlled devices once gain and offsets were confirmed. This ensured that the computer system would not start initialization of the sample until the proper confining stress and deviatoric stress were established. Although the system is capable of applying initial stresses via feed back loops, this automated procedure often led to erroneous stress. Therefore, the third step was to manually apply the initial stresses and then start allowed better calculation of sample height and maximum dry density, all of which helped to define each specimen and ensure the specimen started at the proper conditions.

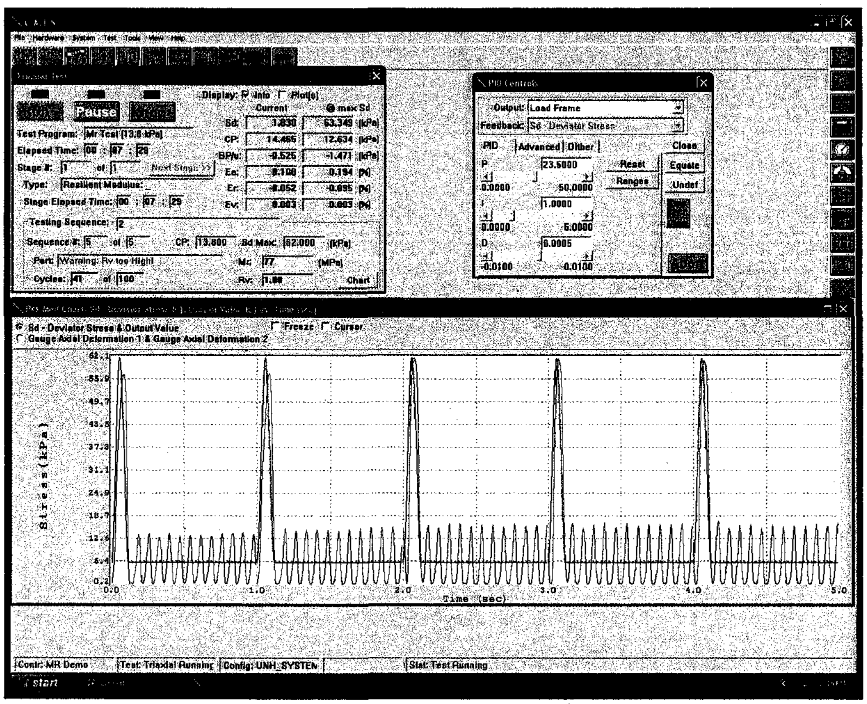


Figure 4.4: M_R Harmonic Response Example

4.6.3 PID Controls

The second step to ensuring repeatable results is the constant monitoring of the PID controls. During a M_R test, a pre-established haversine load is applied for 0.1 seconds and then unloaded for 0.9 second then loaded again. For each of the 15 M_R cycles, this sequence is repeated 100 times. A user has two options to modify the load applied, Peak-Valley or PID. The first option is an automated check. The testing software uses a program known as "Peak-Valley Compensation". During this automated check, the GCTS system slowly modifies the computerized initialization sequence. The closer the starting stresses were to the desired initial settings the less likely the computerized system was to over-correct and apply erroneous force.

A beneficial side effect of manually initializing the sample is the proper sequence order. As required by AASHTO standards, the confining pressure must be established prior to initial seating pressure, or contact pressure, of the deviatoric stress. By first manually producing the confinement pressure then the seating pressure, it was possible to ensure this required sequence was met. Because the computerized system is designed for continuous feedback from both load cell and cell pressure, the system tries to modulate both at the start of the test and a harmonic resonance was observed numerous times. Simply put, the deviatoric stress influences the cell pressure and vice versa. Trying to synchronize both at the same time led to a negative response that carried over into testing. Figure 4.4 is an example of a harmonic sequence captured on screen in the GCTS control panel. This harmonic response subjected a specimen to undesired stresses and invalidated protocol assumptions. However, unless the response resonated, causing the sample to fail, it could be mistaken as a valid test by all other AASHTO requirements. Preventing this type of behavior, and others, was the reason for manually starting the test. Preventing this type of situation, through the in-house startup procedure, was an instrumental step in producing repeatable results.

The startup procedure established also allowed for additional measurements, not required by AASHTO, to be taken prior to testing. This data the hydraulic pressure to achieve the desired results. By using feedback loops, the system can modify the hydraulic pressure and then add/subtract fluid to ensure the proper stress is applied to the sample. For example, the peak control limits the stress of the load cycle from exceeding AASHTO standards. If the applied load does exceed the standard, the applied peak load is reduced slightly for each following repetition. At the same time, the valley control ensures the required minimum contact stress is maintained during the 0.9-second unloading.

Figure 4.5 shows a test sequence with and without the compensation tool. The first frame in the figure shows a sinusoidal unloading that exposes the sample to not only stress below the required contact pressure but also to negative contact stress resulting in erroneous stress and possible sample deformation. The second frame shows both these problems resolved by the computerized peak-valley tool. Fine-tuning the load sequence proved very helpful and prevented erroneous data collection.

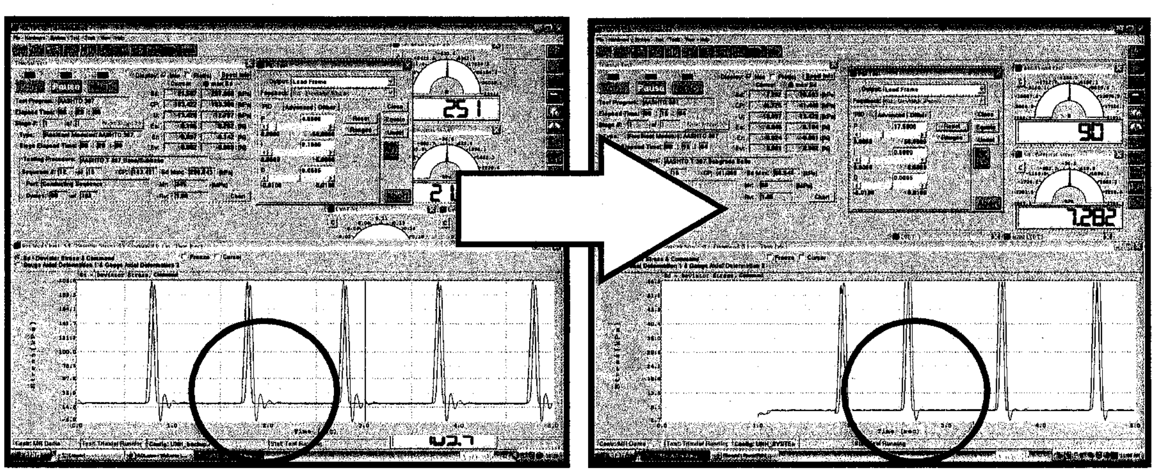


Figure 4.5: M_R Examples Without and With Peak-Valley Compensation preventing negative principal stress (note change in y-axis scale)

The peak-valley compensation tool makes very small incremental changes. Therefore, it is possible for the compensation tool to take much longer than 100 repetitions to achieve the desired haversine peak and valley loads. The M_R is recorded and calculated from the stress and strain of sequence 96, 97, 98, 99, and 100, and even if the proper loads are achieved by sequence 95, the sample has not been properly stressed during the 95 previous sequences. As a result, future cycles are not an accurate representation of the strength or resilience of the material, leading to erroneous M_R data.

Consequently, it is important to manually aid this process via the second control option PID. With the PID gain controls, a user can modify the "Peak", "Intensity", and "Duration" of the loading sequence. However, in a M_R test, the duration is set by AASHTO standards at 0.1 seconds and therefore adjustment of the duration gain does not affect the sequence. For the same reason, the applied load in haversine form by AASHTO standards means the intensity gain is not a variable function either. The peak gain, however, can quickly adjust the applied load to match the required load within 5 to 10 sequences.

The first frame of Figure 4.6 shows an applied load (black) that is much larger than the AASHTO required load (blue). The second frame shows this load after adjusting the peak gain control where the proper load is applied to the sample. Quick and proper adjustment of the peak gain control is a vital step in producing repeatable results. Experience showed that the control must be used in the early stages of the cycle (sequence 25 or less) to achieve proper results and prevent numerous sequences of overloading or under-loading. In addition to manual PID, the use of a peak-valley compensation tool was crucial to prevent sinusoidal response during the unloading period and to prevent reduced contact stress. Use of both techniques during testing helped to decrease deviation.

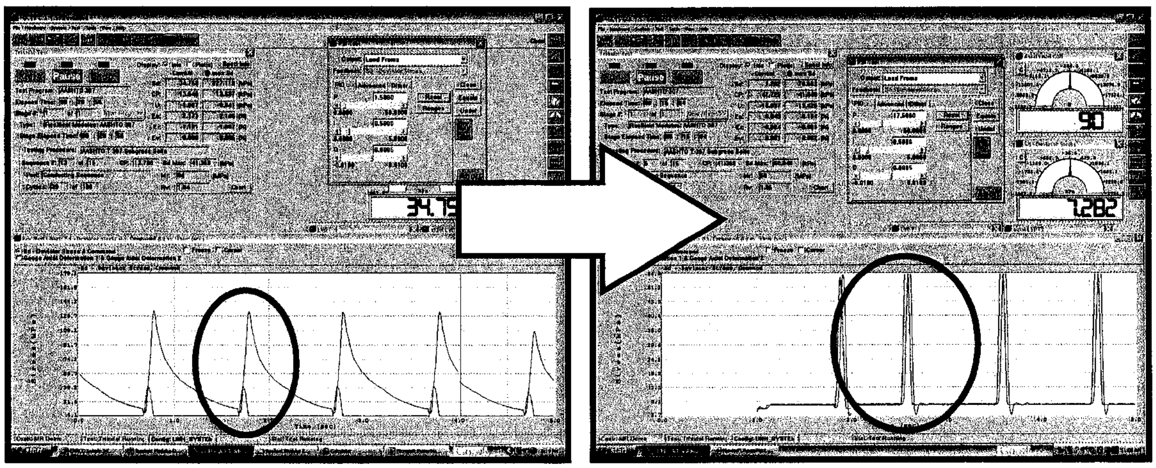


Figure 4.6: M_R Examples of Peak Gain Control Used to Adjust Load Amplitude to match AASHTO required load (note change in y-axis scale)

4.6.4 Blank Testing and Hysteresis Check

After all components of the GCTS passed calibration, a confirmation test with a rubber insert was conducted. This insert is known as a rubber blank and allows the system to run at full capacity without the possibility of specimen failure to confirm M_R testing is ready for data collection. The rubber blank allowed for checks in the load cell setup, LVDTs placement and setup, proper confining stresses, AASHTO load sequence, and computer data collection.

The next step performed was a steel insert, or steel blank. This blank is an exact specimen replica made of A36 steel. Because the loads used in M_R are based on soil strength, the maximum deviator stress is 40 psi. Hence, the steel blank, with F_Y = 36 ksi, does not deform significantly under the load. Therefore, any recorded deformation is due to flexure of the GCTS system and recording instruments. By using the blank, it was possible to confirm if system flexure was of concern in the data collected. Results of both the rubber blank and steel blank are presented in Figure 4.7.

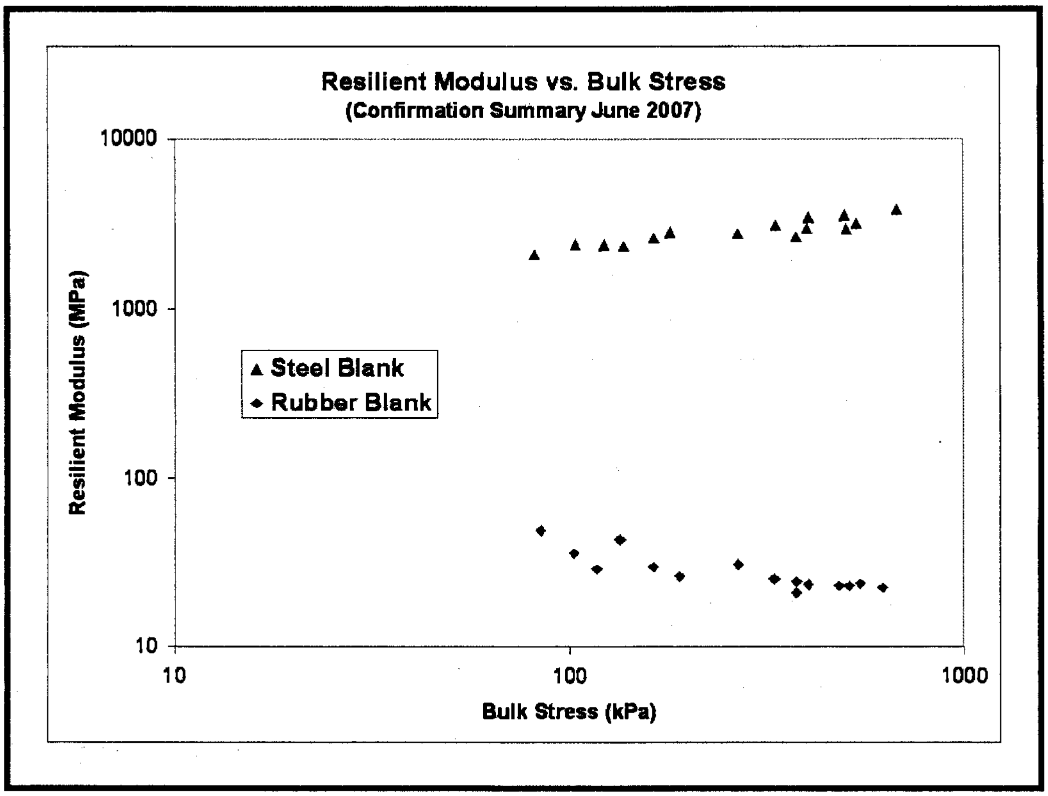


Figure 4.7: Resilient Modulus versus Bulk Stress (Steel and Rubber)

As Figure 4.7 shows, the magnitude of M_R from the steel blank is well over 2000-MPa. In comparison to the range of expected M_R results, maximum of 700-MPa, the steel blank confirms that erroneous data from machine yielding is not of concern for this research.

The final check prior to conducting research testing was to run a full M_R test on a sample material. This final test was to confirm all GCTS systems were functioning properly and stresses applied to the sample were acceptable. In addition, this test provided data to confirm elastic behavior in the sample. By taking the raw data from the M_R test, a stress-strain curve was plotted for the first five cycles, cycle 1 through cycle 5. If the Elastic Modulus, or slope of the curve, was the same for each cycle, then the sample was behaving elastically. Figure 4.8 shows the hysteresis plots for Sample 1-22, and graphically illustrates the Modulus of multiple cycles confirming the elastic behavior during testing and absence of permanent strain.

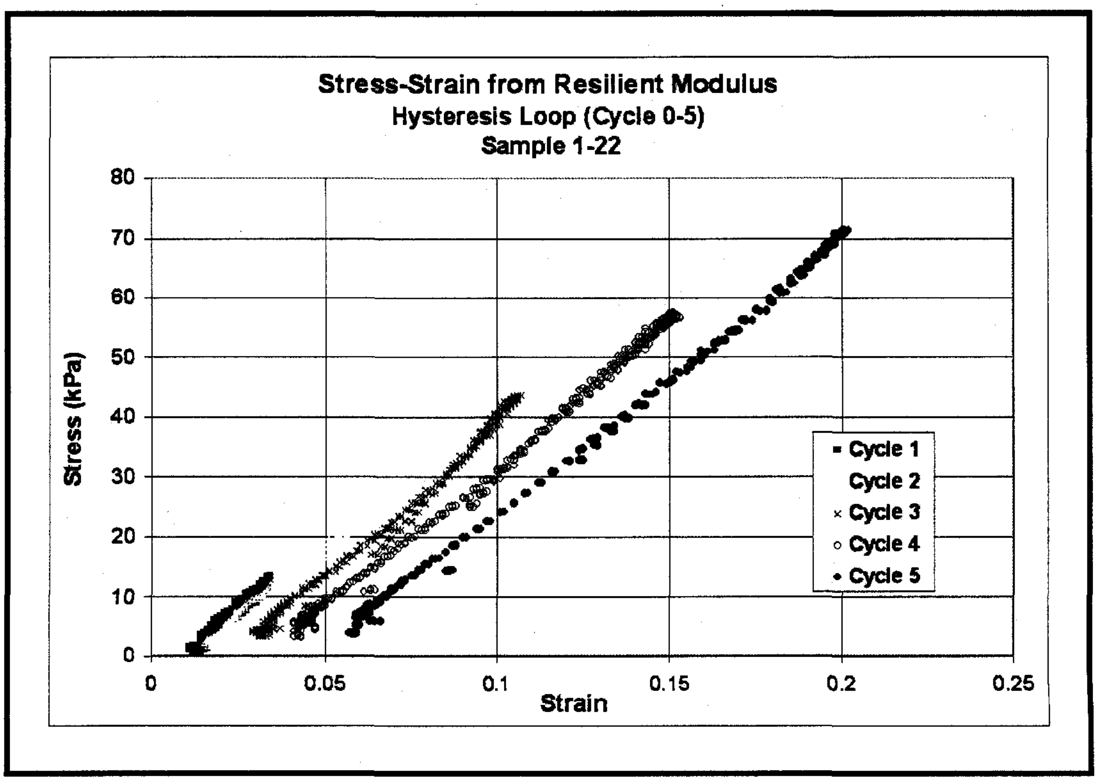


Figure 4.8: Hysteresis Loops for Sample 1-22

4.6.5 Testing Results

After establishing startup procedures, hands on training with GCTS trainers, and countless practice tests from January to May 2007, the research tests were preformed from June to September 2007. Table 4.6 shows the M_R testing results for all final tests, the average values, and deviations. All M_R testing results are presented in Appendix E.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ME-1	409.61	340.90	375	9.16%
ME-2	623.43	662.29	643	3.02%
ME-3	318.76	295.72	307	3.75%
ME-4	135.49	202.70	169	19.87%
ME-5	217.68	217.54	218	0.03%
ME-6	656.62	517.75	587	11.83%
ME-7	286.34	355.81	321	10.82%
	379.78	381.77	381	0.26%
	281.40	324.28	303	7.08%
	154.77	159.35	157	1.46%
	140.14	135.41	138	1.72%
	137.15	131.93	135	1.94%

Table 4.6: M_R Testing Results for all Samples

It is important to understand where these 24 data points originate. Each M_R test is actually the evaluation of the same sample at 15 different deviatoric and confining stress combinations. Consequently, each M_R tests actually produces a series of 15 data points (1 per cycle). Each data point being the average of the last five sequences per cycle. These 15 data points give not only the M_R value for each combination of stresses, but also show trends in the data. For example, the first frame of Figure 4.9 shows the 15 data points of bulk stress (σ_1+σ_2+σ_3) and resilient modulus (σ_d/ϵ_R) for ME-4 Sample #1. The second frame shows this data plotted as log resilient modulus versus log bulk stress.

Reduced Data from Testing
ME-4 Sample #1 (27 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd o/o	=Mr/1000
	(kPa)	(MPa)
Sequence	θ	Mr
1	78.501	91.540
2	100.857	84.468
3	120.859	89.469
4	134.813	95.500
5	168.759	97.602
6	205.699	111.138
7	271.590	118.721
8	338.290	148.908
9	400.387	186.491
10	373.223	113.215
11	408.042	130.994
12	506.063	202.963
13	509.719	141.059
14	543.698	167.116
15	679.987	253.174
	Average	135.5

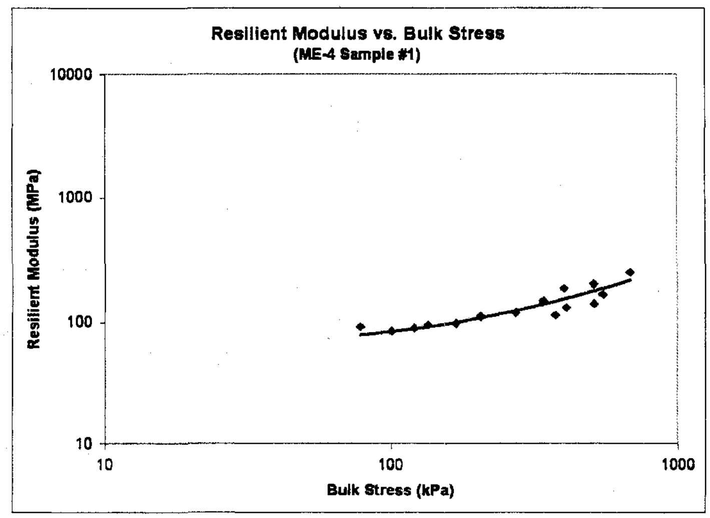


Figure 4.9: M_R Test Data and Resilient Modulus versus Bulk Stress (ME-4 Sample #1)

The first step in analyzing the data is to determine the average M_R for the test. The bulk stress is defined by AASHTO standards and therefore serves as the input variable in the test; the output of the test procedure is the M_R for each sequence. The average M_R is used to represent the samples' 15 cycles. As discussed in Chapter 3, the LTPP and MEPDG cannot use a generic average of M_R for Level-1 input because the average does not correspond to a specific deviatoric and confining stress combination. However, it is possible to use the average M_R value for Level-2 input and comparative analysis because all samples are tested with the same stress combinations.

Reduced Data from Testing
ME-6 Sample #2 (22 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Sequence	θ	Mr
1	90.859	890.880
2	101.942	433.803
3	116.435	284.047
4	139.236	791.797
5	162.188	346.318
6	199.535	306.989
7	270.569	507.296
8	322.948	367.793
9	377.033	323.275
10	370.951	712.476
11	395.555	513.632
12	511.408	462.867
13	506.145	681.426
14	544.787	627.454
15	704.915	516.224
	Average	517.8

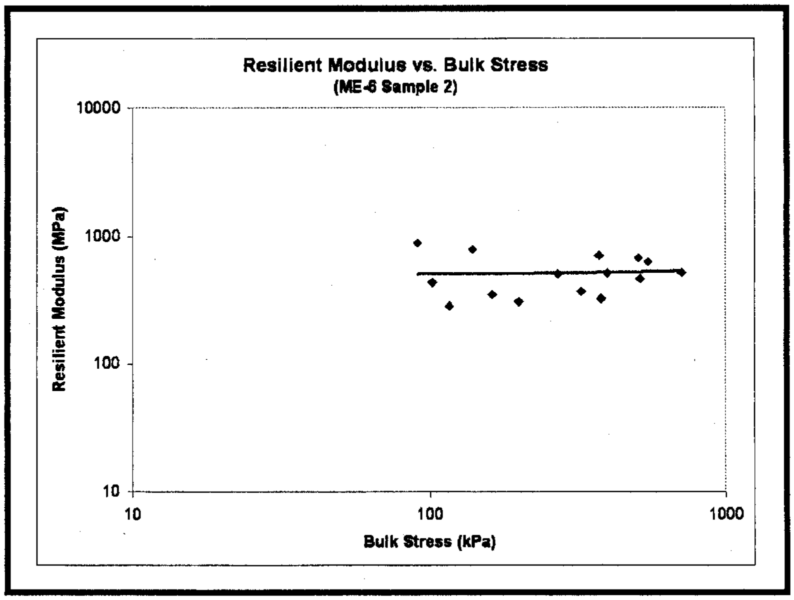


Figure 4.10: M_R Test Data and Bulk Stress versus Resilient Modulus (ME-6 Sample #2)

The second step in analyzing the data is to evaluate the plot trends of the sample. In this case, Figure 4.10 shows an increase in M_R with an increase of bulk stress. Therefore, as confining pressure increased, the sample became proportionally stiffer despite an increase of deviatoric stress. Not all samples showed this trend. For example, Figure 4.10 shows a data set, ME-6 Sample #2, which maintained the same M_R as bulk stress increased. Again, as confining pressure increased, the rigidity remained proportionally the same as deviatoric stress increased. It would also be possible for a sample to trend with decreasing M_R as bulk stress increases. However, for the most part, this also coincides with long-term plastic deformation and the sample failing at 5% strain.

The average M_R ranged from a low of 135-MPa (ERRCO-4) to a high of 643-MPa (ME-2) and all samples met the deviation cutoff of 20%; albeit ME-4 just barely at 19.87%. The M_R for natural materials was highly variable ranging from 169 (ME-4) to a high of 643. This does not follow the same pattern seen in the CBR testing where natural materials had very similar results. This suggests that high quality fill, defined by CBR and strength alone, does not represent material with high M_R.

Notably, this contrast was exactly what concerned contractors with roadway design based on CBR testing alone. Therefore, despite using strong, high quality material for base/subbase application, the road might still experience high settlement, cracking, and rutting after vehicular use. Whereas a CBR test does not quantify this type of information, the M_R does.

The two important ways M_R testing quantifies this information to the user is by removing permanent deformation through pre-conditioning and by plastic strain monitoring. First, by pre-conditioning a sample with 500-1000 sequences of "traffic" load before the test starts, it is possible to evaluate the long-term elastic resiliency of the sample. For example, if a material has a high elastic strain at a given deviator stress it will result in a lower M_R than another sample at the same deviator stress with less elastic strain. Although ideally both samples could carry the same static load, the material with the higher M_R would have less permanent deformation and therefore fewer surface cracks and decreased rutting. Second, the entire plastic deformation over the M_R test is measured and the sample fails if plastic strain exceeds 5%. This is an indication, that despite

CBR strength, the material will deform excessively after being placed into service.

Figure 4.11 graphically shows the average M_R for each sample to help identify possible trends. One notable trend, the three materials that were 100% C&D debris (ERRCO) were significantly lower than most samples and the three lowest of all samples. However, the same cannot be said for the blended C&D debris samples, which had very high M_R (303-MPa & 381-MPa).

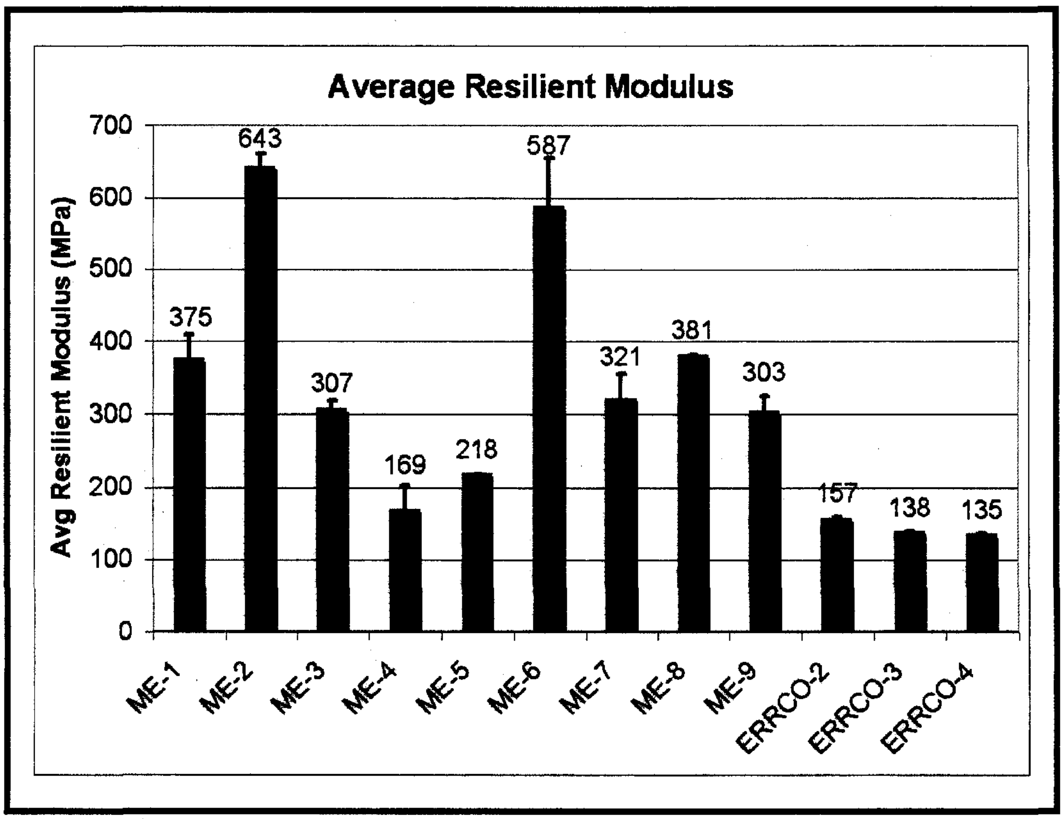


Figure 4.11: Average Resilient Modulus for all Samples

Unfortunately, the very small deviations in ERRCO M_R results prevent statistical analysis since 25% deviation is common in M_R testing. Even with the very small deviations seen between the ERRCO samples, all less than 2%, the extremely close results do not allow for brick and wood effects to be analyzed.

By first evaluating ME-6 and ME-7 and then comparing them to their blended C&D debris counter parts; it is easy to see the same trends from CBR testing do not apply. In CBR testing, ME-9 resulted in a 5% reduction from ME-6 and ME-8 a 40% reduction from ME-7. In the M_R testing, the exact opposite was true. ME-9 produced a 63% reduction from ME-6, while ME-8 produced only a 17% reduction from ME-7. Add to the deviations, the 25% variance found in M_R testing, and only the change in ME-6 to ME-9 is statistically important.

If the change in ME-6 & 9 was due to a reduced strength in the C&D debris, why was it not seen in CBR testing? Moreover, why was the large reduction in CBR bearing strength between ME-7 & 8 not seen in the M_R testing? The first answer is that bearing strength and modulus of elasticity are not always correlated; usually, but not always. The second answer is that CBR and M_R are often correlated, but as Section 4.6.6 testing will show, that relationship is not as sound as Equation 2.7 would suggest. Therefore, the association of CBR and M_R is closely evaluated in Section 4.6.6.

4.6.6 CBR Predictive Model Results

Simply taking the CBR predictive model and evaluating the correlation between CBR and M_R suggests that as the CBR increases, M_R will always increase. However, remembering that this model is a best-fit representation of 4,000 data points by DOTs, it is important to compare the actual data in some detail. Equation 2.7 is the conversion equation, or predictive model, of CBR value to M_R in units of psi.

$$M_R = 2555(CBR)^{0.64} \qquad \text{(Equation 2.7)}$$

Using Equation 2.7 to predict the M_R results for this research data allows the direct comparison of CBR and M_R for each sample. Figure 4.12 shows the average predicted M_R (based on Equation 2.7) and the average actual M_R (based on testing). In order to keep units consistent, all M_R results are shown in MPa.

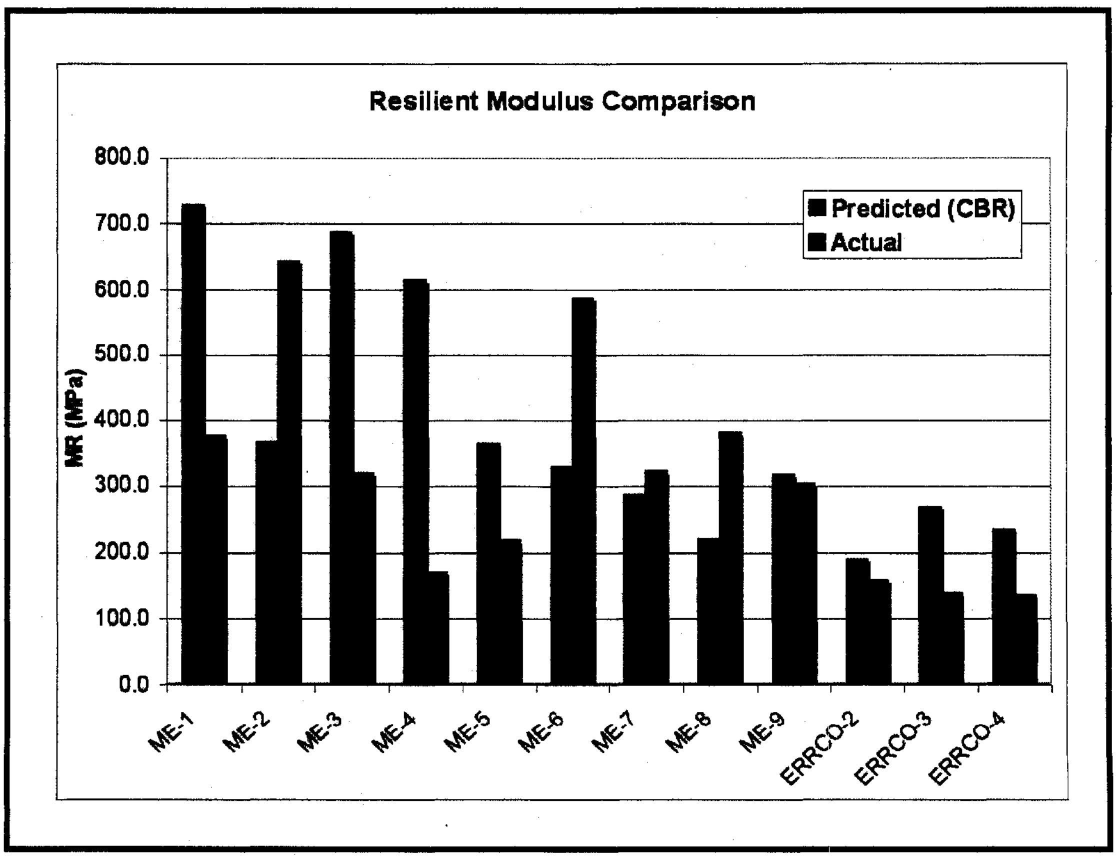


Figure 4.12: Predicted M_R and Actual M_R for all Samples

The first trend that is noticed between predicted and actual M_R is that there seems to be no trend. Some of the predicted M_R values are much higher than the actual values (ME-1, ME-3, ME-4, and ME-5), some of the predicted are much lower (ME-2, ME-6, ERRCO-3, and ERRCO-4), and some are approximately correct (ME-7, ME-9, and ERRCO-2). There does not appear to be a correlation with lower values being closer as ME-4 is the largest in deviation. While the model is based only on natural materials with CBR values ranging from weak subgrade to high quality base, it is interesting that the five recycled materials have a much smaller deviation than the seven natural samples. The model does not appear to be an accurate way of predicting the M_R for base/subbase materials, and therefore should not be used for designing roadways with C&D debris in that capacity.

Take for example ME-1, with a predicted value of 728 [MPa] and an actual value of 375 [MPa]. If an engineer used the CBR model for design purposes, the material placed on the job site would actually have only 52% of the expected strength. This large deviation reveals some insight to Mr. McClay's comment from the Maine DOT about CBR values over 100%. Is it possible for a soil to have a CBR of 800%? If the results for the predicted M_R are limited to a maximum CBR value of 100%, then the predicted value is limited. Although this conveniently pairs some of the data, Figure 4.13 shows that this data does not have a more accurate correlation. Limiting the input data in this manner also does not address the cases were the actual M_R is less than the predicted.

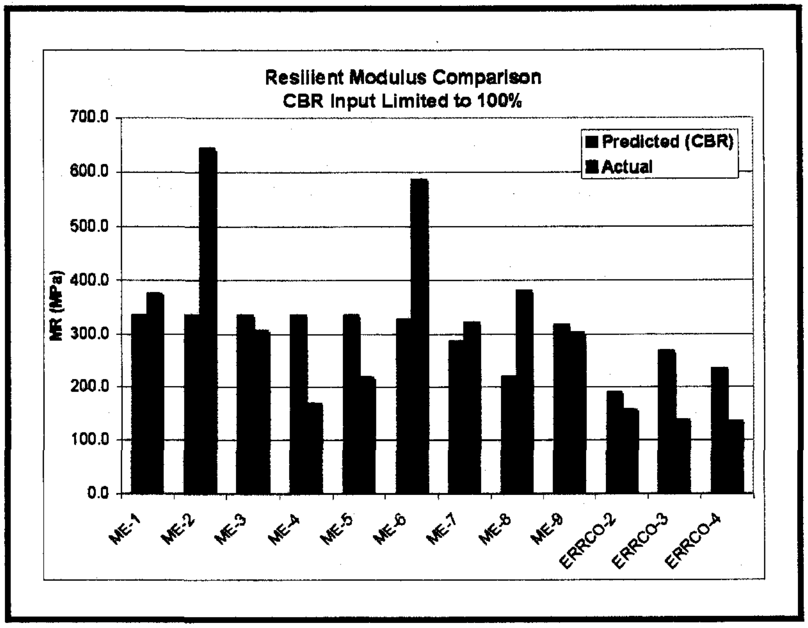


Figure 4.13: Predicted M_R and Actual M_R for all Samples with CBR Limited

Instead, it may help to evaluate the data another way. Figure 4.14 shows the evaluation of data when comparing the model results with the actual results. Clearly, the model does not represent this data with an R^2 value of 0.01.

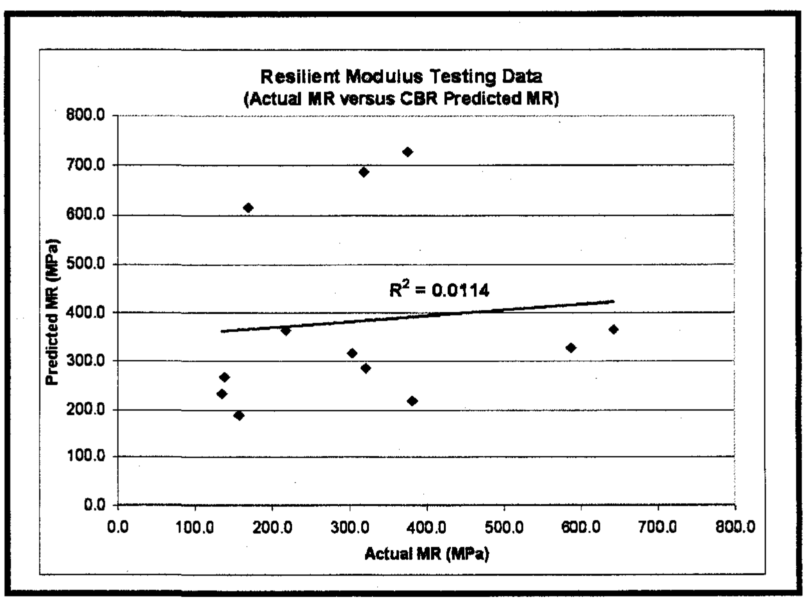


Figure 4.14: CBR Predicted M_R versus Actual M_R

However, the CBR to M_R was based primarily on fine-grained materials. Similar to the WisDOT findings about the LTPP data, the model decidedly does not fit coarse-grained materials as well.

Figure 4.15 graphically shows that the lower the CBR the better fit to the predictive model even with these coarse-grained materials. The samples with CBR in the range of 45% to 100% appear to follow the model much better than the samples with CBR over 125%.

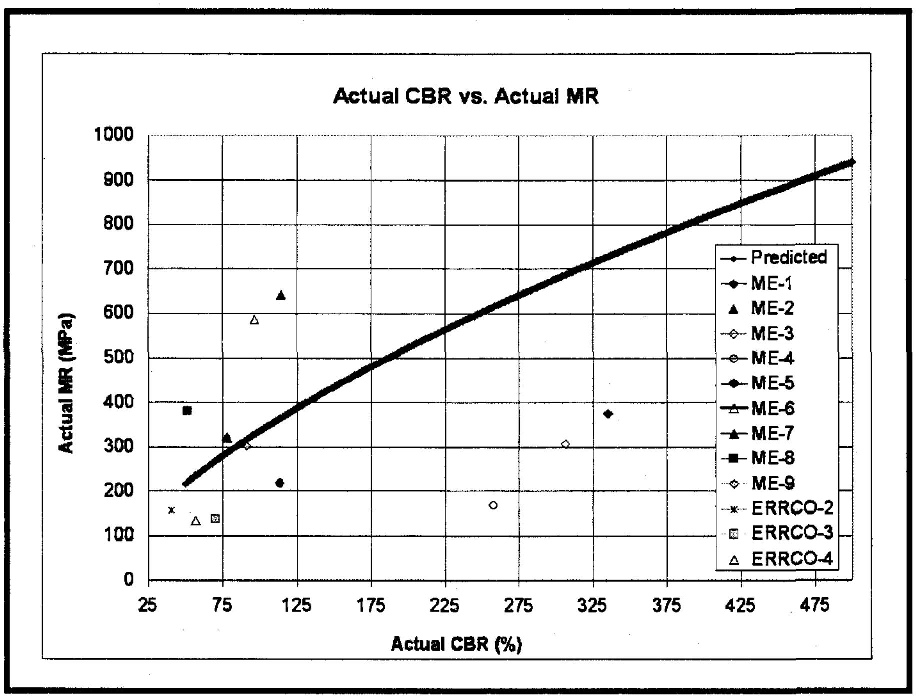


Figure 4.15: Actual M_R versus Actual CBR with Predicted Equation Plotted

4.6.7 Modified Equation Model Results

4.6.7.1 K-Values from Modified Equation. DataFit software was used to perform regression on the M_R research data to determine the K_1, K_2, and K_3

variables of the M_R modified equation. The modified universal equation, Equation 2.6, models the 15 bulk and deviatoric stress combinations of the sample to represent the behavior of the sample. Therefore, regression of the 15 data sets determines the K-values and the statistical data associated with fitting the model.

$$M_R = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \cdot \left[\frac{\tau_{OCT}}{P_a}\right]^{K_3} = K_1 P_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sqrt{2}}{3}\frac{\sigma_d}{P_a}\right]^{K_3} \quad \text{(Equation 2.6)}$$

Regression was performed on each sample (15 data points) and then again on each sample set (30 data points). For example, regression on ME-4 Sample #1 yielded K-values that fall within the LTPP guidelines and with a R^2 value of 0.91. This suggests the model accurately represents the data and follows the same trends that the ETG found in their research. Regression on ME-4 Sample #2 also yielded K-values that fall within the LTPP guidelines and a R^2 value of 0.94. However, when the 30 data points are combined, the resultant regression produces a K_3 value outside of the LTPP guidelines and a R^2 value of 0.66. Therefore, despite accurate model representation of each sample the combination is not accurately modeled by the equation. Although the K-values are statistically determinate, the modified equation for the combined data is not statistically representative. Table 4.7 shows the regression results, to include K_1, K_2, K_3, and R^2, for all samples.

Of the 24 M_R tests, only five meet the NCHRP guidance of $R^2 \geq 0.90$. This does not mean the M_R is not accurate or valid, but rather in general coarse-grained soils are not accurately modeled with the MR modified universal equation. In addition, only one material, ME-4, had both samples with regression statistics meeting the guidelines. However, despite the model not accurately representing the data, the K-values for each of the natural samples still follow the LTPP guidelines for trends and value range. This indicates the material behaved in the same manner found by the ETG. The K-values for both blended recycled materials also followed this same trend. Conversely, the K-values for the six 100% C&D debris tests were all outside the guidelines for the LTPP data. This suggests that the material did not respond in the predicted manner.

	ME-1		ME-2		ME-3		ME-4		ME-5		ME-6	
	ME-1-1	ME-1-2	ME-2-1	ME-2-2	ME-3-1	ME-3-2	ME-4-1	ME-4-2	ME-5-1	ME-5-2	ME-6-1	ME-6-2
[illegible]	1.83	1.10	3.86	5.19	1.19	1.74	1.13	1.14	1.21	1.32	1.43	2.42
[illegible]	0.50	0.97	0.60	0.43	0.52	0.44	0.18	0.53	0.53	0.46	0.76	0.57
[illegible]	-0.91	-0.74	-0.45	-0.22	-1.18	-0.41	0.38	0.08	-0.07	0.00	-2.01	-0.80
[illegible]	0.36	0.94	0.74	0.64	0.65	0.19	0.91	0.94	0.79	0.71	0.89	0.53

	ME-7		ME-8		ME-9		ERRCO-2		ERRCO-3		ERRCO-4	
	ME-7-1	ME-7-2	ME-8-1	ME-8-2	ME-9-1	ME-9-2	ERRCO-2-1	ERRCO-2-2	ERRCO-3-1	ERRCO-3-2	ERRCO-4-1	ERRCO-4-2
[illegible]	1.78	2.20	2.97	2.09	1.32	1.77	0.80	0.80	0.69	0.93	0.93	1.10
[illegible]	0.44	0.42	0.40	0.37	0.67	0.50	-3.54	-0.57	-2.53	0.36	0.36	0.18
[illegible]	0.04	-0.25	-0.43	-0.80	-0.22	-0.51	2.85	-0.58	-0.58	0.21	0.21	0.46
[illegible]	0.86	0.38	0.43	0.67	0.99	0.44	0.77	0.81	0.84	0.87	0.87	0.92

Table 4.7: Modified Equation Regression Results for all M_R Samples

While some materials had one sample with an extremely high R^2, the other sample had a very low R^2. Take for example, ME-1 and ME-9. Each material had one of the samples with R^2 of 0.94 and 0.99, while the second sample was 0.36 and 0.44 respectively. Both of these materials had average M_R over 300-MPa and therefore would be qualified as high-grade materials. In contrast, four samples fit the M_R modified equation far better than other materials. ME-4 and ERRCO-1, ERRCO-2, and ERRCO-3 all have R^2 values above 0.77 for both samples. Accordingly, it appears that the lower strength materials fit the M_R model better. Predictably, these results coincide with the WisDOT findings.

Recalling that the M_R models originated from the 2,500 LTPP data sets, it is important to note that only 180 of those data points represent base/subbase materials and the remainder are subgrade materials. Thus, the LTPP model was decidedly biased for subgrade materials. Therefore, it is not surprising to find the materials with lower strength values are better represented by the M_R model.

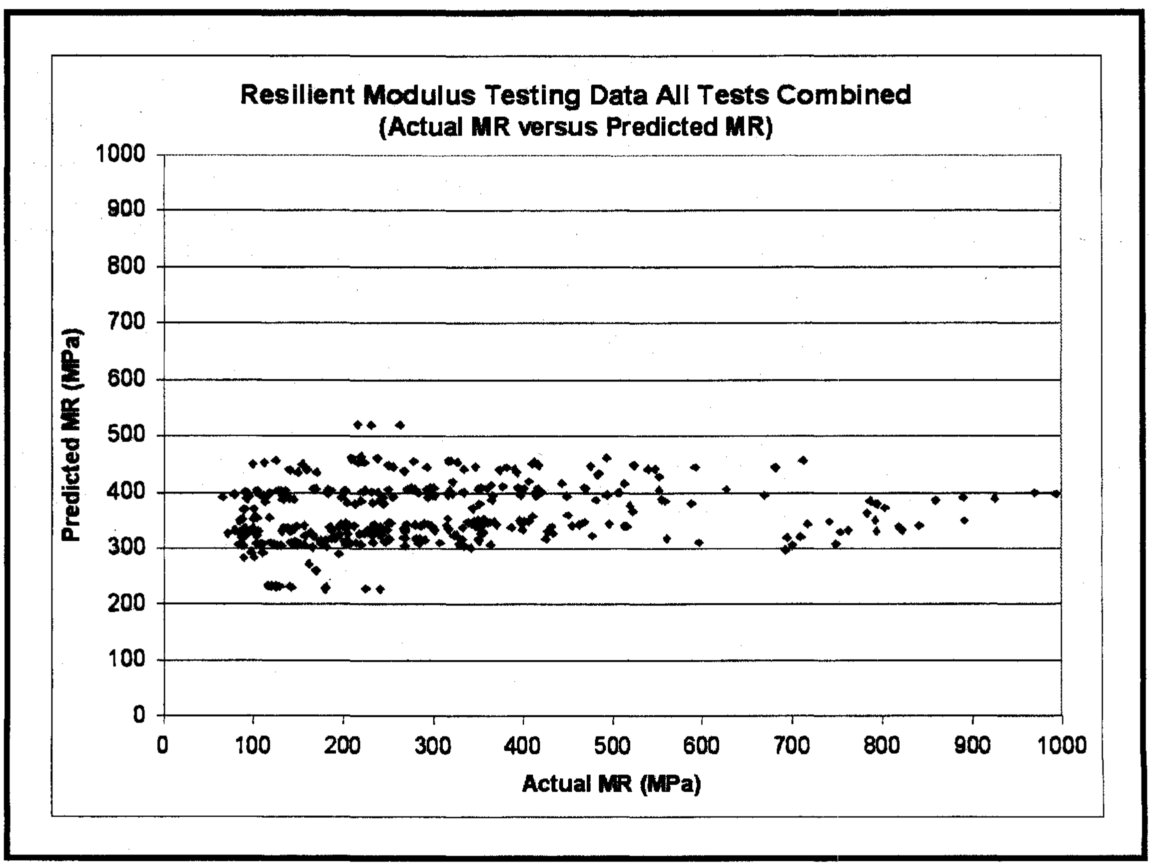


Figure 4.16: Predicted M_R versus Actual M_R (All Cycles)

Despite the modified universal equation having poor statistical representation of most of the samples (19 of 24), there is still one step that should be performed to evaluate the modified equation with the research data. Although each M_R test consists of 15 data points, it is common to average the value to one point to represent the sample. Remember, the average of the 15 cycles was used from the actual testing and for MEPDG Level-2 input. Figure 4.16 shows all 360 data points when comparing actual M_R versus predicted M_R. As expected from the corresponding R^2 values, the model does not appear to represent the data.

However, using this same methodology and disregarding the R^2 values momentarily, the K-values from each sample were used to calculate the predicted M_R for each of the 15 data sets. Then, just like the actual data, the average of the predicted M_R is used to represent the sample. The modified model did not statistically reflect the 15 data cycles as the data itself was highly fluctuating and only one material had an $R^2 \geq 0.90$ on both samples. When statistically evaluating the match of average predicted M_R versus average actual M_R, the model provides an adequate representation of the data. Figure 4.17 shows the actual M_R average versus the predicted M_R average.

Despite the poor fit of the modified equation for individual stress cycles for each sample, the modified equation matches the actual averages very well with a R^2 of 0.93. It is therefore plausible to use the universal equation to predict an average M_R value for coarse-grained material despite inaccurate modeling for the stress combinations.

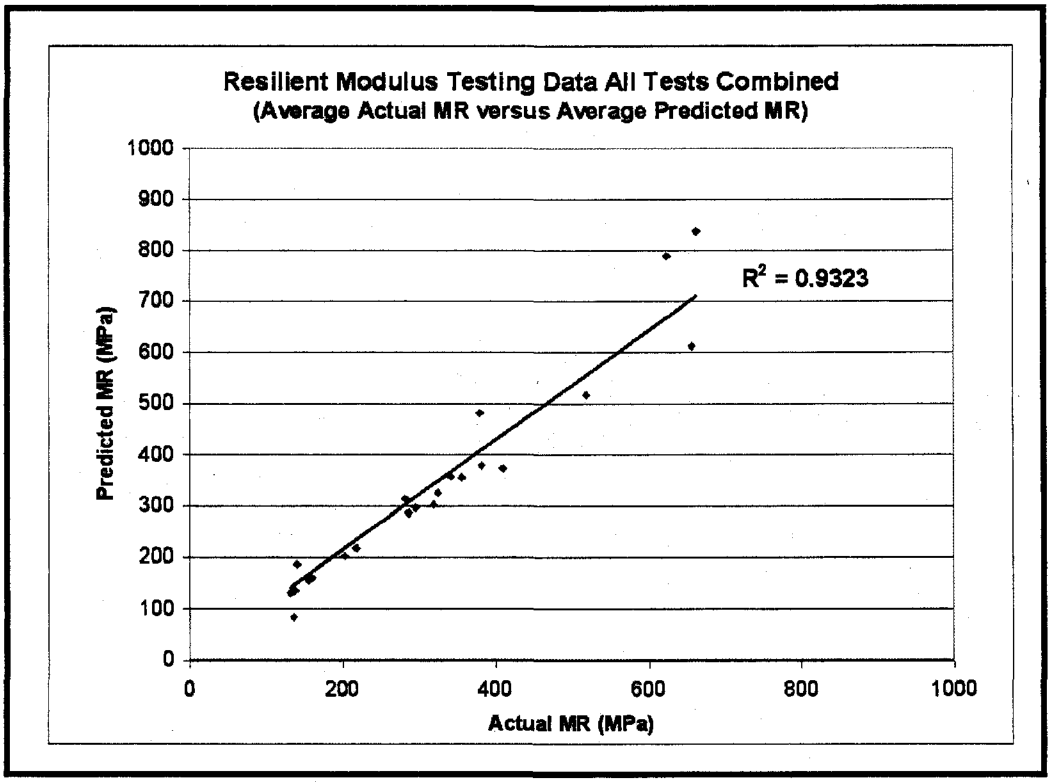


Figure 4.17: Average Actual M_R versus Average Predicted M_R

4.7 Mechanistic-Empirical Pavement Design Guide

4.7.1 MEPDG Road Design

The next step in roadway design, once laboratory testing is complete, is to use a model and determine layer requirements based on material properties. However, for the sake of research, the exact opposite was the next step. In an effort to hold all variables constant and evaluate the effect of the base/subbase materials, a uniform base thickness of 15-inches was used for all models. As described in Chapter 3, the goal of using the MEPDG was to use the exact same base model for all tests and only change the CBR value or M_R of the layer to capture the effects. Therefore, instead of using the MEPDG to design the correct layer thickness to prevent cracking, the design guide was used to estimate the cracking based on constant thickness and to evaluate comparative results.

4.7.2 MEPDG Road Simulation

In an ideal world, to evaluate the affect of each sample material on roadway performance, actual test road sections with different base/subbase materials would be used, while holding all other variables constant. However, this would require vast amounts of material, space on either an active road or test site, and five or more years to evaluate performance. All of this associated with additional cost. The second is a simulation of the same procedure. Simply put, the current understanding of long term effects of C&D debris does not justify the time, space, or money at this point in time. Simulation testing was used to evaluate the materials in the roadway. While the MEPDG serves as the current state-of-the-art practice in roadway design, it also serves as the modern standard for roadway simulation.

The first piece of information needed was to understand the simulation boundaries with the base model. A trial simulation was conducted at the maximum and minimum values for both CBR and M_R. Table 4.8 shows the simulation results for these extreme cases. Interestingly, the minimum and maximum CBR values do not correspond to the M_R values. For example, using CBR input, the minimum value possible to enter is 1%; whereas the minimum value for M_R is 500-psi. Using the CBR-M_R conversion equation, a CBR of 1% corresponds to a M_R of 2555-psi. As a result, the expected rutting for the minimum M_R would be much greater than the CBR minimum. The same holds true for the maximum values. The maximum CBR is 100%, while the maximum M_R is 5,000,000-psi. To establish the rutting limits of the MEPDG program, the minimum and maximum values of both CBR and M_R were used in the base model.

Base Model with 10-year Simulation	[illegible]	Rutting [illegible]	[illegible]	[illegible]
Minimum Value	1	0.923	500	1.635
Maximum Value	100	0.640	5000000	0.580

Table 4.8: MEPDG Minimum and Maximum Values with Corresponding Rutting at 10-year

The final step in the MEPDG was to analyze each sample for both CBR and M_R. This is an important step as it defines the actual effect of the difference in CBR and M_R with respect to design. Obviously, ME-1 is the same material used in both CBR testing and M_R. However, what does the stark difference in expected M_R, when predicted with CBR, and the actual M_R mean? Does one of these values result in over-design or under-design? Table Figure 4.18 is the summary of all simulation testing for both CBR and M_R.

Based on the predicted M_R, 728-MPa, and actual M_R, 375-MPa, from sample ME-1, logic would suggest that the same disparity would be seen in the rutting. However, this disproportion is not apparent in the simulation. One reason for the decreased difference in rutting is the maximum CBR value. Despite having a CBR value of 335% and predicted M_R of 728-MPa, the MEPDG runs the simulation with a CBR value of 100%. Consequently, the design strength would instead be approximately 335-MPa and very close to the actual M_R of 375-MPa. Therefore, any sample whose CBR value resulted in a higher predicted M_R than actual M_R will appear to have a better fit in the simulation. This is not actually the case, but rather a mathematical limit of the design model. For that reason, a sample with the opposite situation must be analyzed.

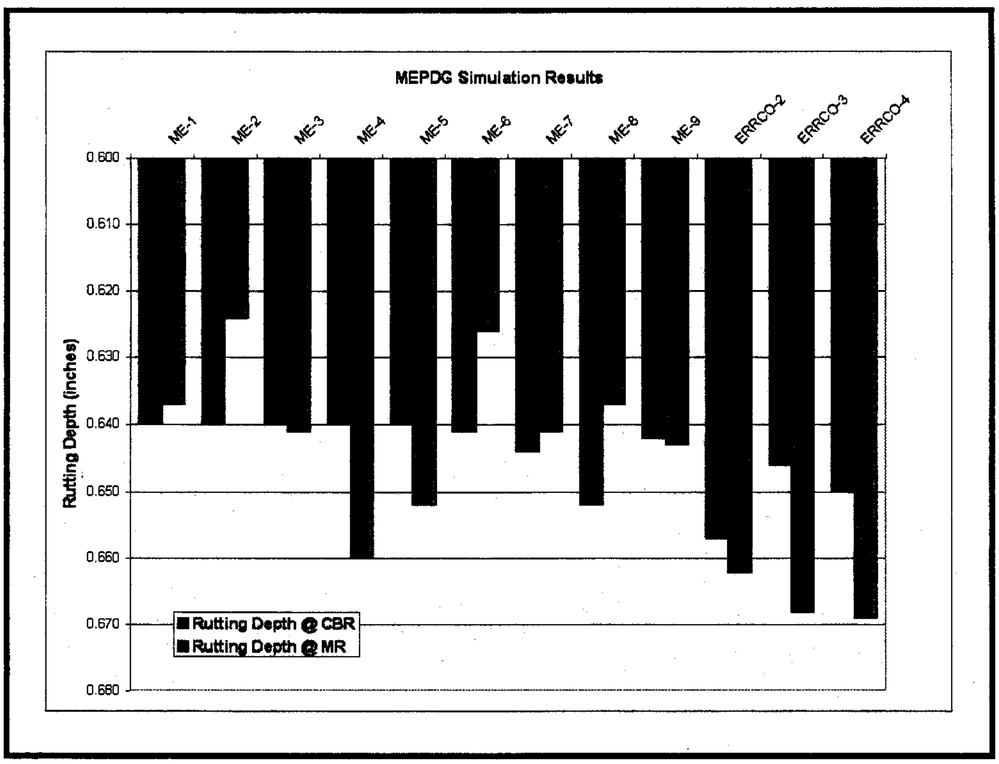


Figure 4.18: MEPDG Rutting Depth for all Samples (CBR & M_R)

When comparing actual M_R to a lesser predicted M_R, ME-2 had the largest deviation. The actual M_R produced a value of 643-MPa compared to the predicted M_R value of 366-MPa, almost a 50% reduction (similar to ME-1) but in the opposite context. In this situation, the deviation is still apparent in the rutting analysis. The same is also true with ME-6 and ME-8. However, a 50% reduction should be mathematically evident in the rutting. Taking into consideration the minimum and maximum rutting (with both predicted M_R and actual M_R) it would be possible to see a 50% increase in rutting potentially associated with a 50% decrease in M_R. However, ME-2 cannot be used for this evaluation simply because the actual CBR value was greater than 100% and therefore limited by the simulation. Conversely, ME-6 had a CBR of 97% and can be considered. The predicted M_R would therefore produce a value of 329-MPa compared to an actual M_R value of 587-MPa. This deviation represents a 44% reduction in M_R. Table 4.9 lists the simulation results of using these M_R figures to determine rutting in the MEPDG.

ME-6	MR (Mpa)	Deviation	ME-6	Rutting (in)	Deviation Corrected
Predicted MR	329	44%	Predicted Rutt	0.641	2%
Actual MR	587		Actual Rutt	0.625	

Table 4.9: ME-6 Deviation of M_R and MEPDG Simulation Results

Even when correcting the rutting deviation for maximum and minimum possible rutting, the 44% deviation does not translate through to rutting. Whether intentional or not, the MEPDG helps consider all of these discrepancies during the simulations. Accordingly, if the MEPDG considers all this, then the data must be evaluated another way.

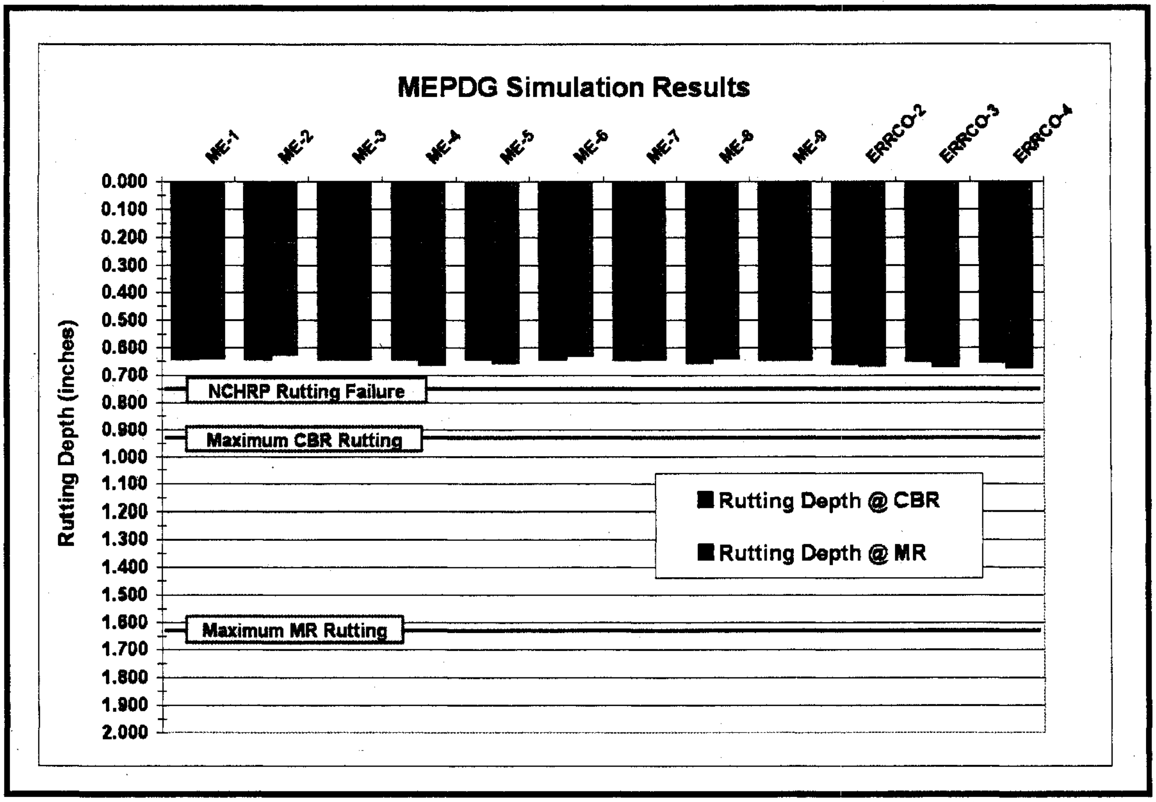


Figure 4.19: MEPDG Rutting Results with NCHRP Failure and CBR-MR Maximum Rutting Lines Annotated

As per NCHRP standards, a rutting failure occurs at deformation ≥0.75-inches. It is possible to fail this limitation with both CBR and M_R minimum values, which could lead to rutting of 0.923 and 1.635-inches respectfully. Figure 4.19 shows the MEPDG simulation results for rutting. Displayed on the figure is the NCHRP rutting failure line and maximum rutting possible for both CBR and MR. For perspective, the scale on the y-axis shows no rutting at the top of the axis and 2.0-inches at the bottom of the axis. The lack of sensitivity in the MEPDG becomes clear when viewed at this level. Despite large variations in CBR values and M_R values, it is easy to see that those variations do not carry over into the MEPDG rutting output.

All 12 samples, both CBR and M_R simulations, meet the NCHRP rutting standard. Just as the seven high performance Maine DOT materials vary greatly in simulation performance, so do the recycled samples. In addition, the three 100% C&D debris samples would result in greater deformation than any of the natural or blended options, but only in the order of 0.029-inches for the worst case.

Originally, the MEPDG simulation was planned for further evaluation by the K-values on all samples. This would create a comparison of samples that met the standard of R2 $\geq$0.90 to samples that did not meet the standard. Because the K-values mostly fell inside the LTPP guidelines for range, this would allow for determining the impact of modeling with the modified equation when it was not an accurate representation. As shown in Section 4.6.6, despite the modified equation not statistically representing most samples at each stress combination, the sample average still produced results that accurately modeled the average M_R. However, the MEPDG is currently not capable of analyzing layers based on K-values, as discussed in Chapter 2 and 3.

4.8 Summary

Using the battery of tests described in Chapter 3, the material properties for all samples were presented in order to clearly identify the types of materials used in this research. This allows future refinement and comparisons with similar materials. Using results of the two key material strength tests, CBR and M_R, repeatability of results and prediction models were evaluated. Finally, simulations conducted with the MEPDG assessed the performance of each material. Every procedure used and every process taken was intentionally meant to use the current state-of-the-art process and evaluate the performance concerning current roadway design.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The objective of this research was to investigate the use of C&D debris in roadway base/subbase application through testing and simulation. This work focused on using the current state of practice for material testing and roadway design to achieve the desired end state.

5.1.1 Material Classification

The current AASHTO standards for material classification adequately and accurately determined the material properties for both the coarse-grained and C&D debris samples. The laboratory results from this research confirmed testing results of two outside agencies. Therefore, the current standards for material classification are more than sufficient for future work with C&D debris materials.

One caveat, is LOI testing. The presence of two materials, organics and bitum, required LOI testing to determine quantities present. Because the furnace ceiling temperature for organics and bitums are the same, ~550°C, any sample tested with both materials present must undergo hand screening and two separate LOIs to determine the volumes in the sample.

5.1.2 Material Strength Testing

Current CBR standards produce approximately 12% variation nationwide with coarse-grained materials. Testing during this research produced variations between 0.1% and 9.5% for natural materials and variations of 0.1% and 12% for C&D debris. As a result, CBR testing proved reliable and very valuable to assess the recycled material. CBR testing can and should be performed on future C&D debris samples.

Nationwide variations for M_R range from 19% to 26% for coarse-grained material, the results from this research showed much less deviation. While one M_R sample showed 19% deviation, the remaining 11 samples were less than 12%, many with only 1-4%. Although the accuracy and repeatability of M_R is in question as an industry, evaluating a material with a test other than bearing ratio provides valuable insight to the materials performance.

For example, one research sample showed a 5% reduction in bearing capacity when blended with C&D debris with a CBR around 95%. This suggests to a DOT that the material is high quality and behaves similar to the original material after blended with C&D debris. However, the same sample produced a 52% reduction in M_R. Despite being a controversial test, in this case, it would provide valuable knowledge about an overly optimistic design assumption. The M_R test should be performed on future C&D debris and is relatively repeatable (±15%) even with coarse-grained and recycled materials.

Following the current testing standards, research testing confirmed the high deviation (±15%) associated with M_R testing. However, the principle use for

M_R is to design a layer thickness with the MEPDG. Results from the MEPDG showed that layer performance is insensitive to even large variations in M_R. In one case from the base model used, a M_R reduction of 50% resulted in only 0.02-inches of additional rutting. This change would correspond to a design thickness change in the base layer that is even smaller. Moreover, that change would be rounded to the nearest inch for ease of construction anyway. Consequently, despite the vast concern for accuracy of M_R, the impacts of the variation are actually minimal. The M_R test, with proper laboratory protocols, should be used for future C&D debris analysis.

5.1.3 Resilient Modulus Predictive Model

Research testing produced an R^2 value for this model of 0.01. This trend for coarse-grained materials has also been reported by research at other universities and DOTs. The M_R predictive model, based on CBR values, should not be used to predict M_R for coarse-grained materials.

5.1.4 Resilient Modulus Universal Model

As NCHRP states in the MEPDG, if the $R^2 \leq 0.90$, then another model should be considered. Clearly, the LTPP testing showed that this model very accurately fits a vast majority of samples. However, this research found a poor correlation for coarse-grained materials as 19 of 24 samples did not meet the 0.90 threshold. This research demonstrated, as WisDOT concluded from their research, the modified universal model is not appropriate for coarse-grained samples. Although, this research did find another productive use for the modified equation: to model the average M_R for coarse-grained materials.

5.1.5 Pavement Design Guide

Just like any software program that is a work-in-progress, until the full version is available to test and review, one must be careful making decisions about the program. The fact that the pavement design guide is more than six years late to market, requires numerous updates just to operate, and is still only 66% complete, makes it hard to speak definitively about the program. Although, the portions that are functioning give valuable insight to the possible performance of a roadway and at the very least give comparative data summaries. For the purposes of this research, the MEPDG was productive and useful. However, its use should be reevaluated after Level-1 inputs are fully functional and compared to an actual field site for accuracy.

5.1.6 C&D Debris Use As Base/Subbase

Despite initial trepidation about using C&D debris as a replacement for natural base/subbase materials, this research conclusively suggests otherwise. While 100% C&D debris options do not provide extremely high bearing capacity or M_R, they do provide strength and modulus that is well above the minimum requirements. At the same time, existing gravel blended with C&D debris produced results as good, if not better, than virgin materials. The idea of "watering down" the natural materials with C&D debris to save local natural resources, transportation costs, and landfill usage is not only environmentally sound, but also economically advantageous. Wherever and whenever the location allows, this option should be investigated and used.

5.2 Recommendations

5.2.1 Factorial Experiment

As Section 4.5.1 (CBR Testing Results) and Section 4.6.4 (Resilient Modulus Testing Results) alluded to, numerous variations in the CBR and M_R could not statistically be determined because many unknowns were changing at the same time. Therefore, a double factorial experiment is recommended. Using the exact same testing protocols (CBR & M_R), select two different gravel materials, and a source of C&D debris concrete, then, test C&D debris blends of 0%, 20%, 40%, 60%, 80%, and 100% for both gravels. Using these 12 combinations would allow for the influence of various amounts of gravel and C&D debris to be evaluated. In addition, by conducting the tests on two natural materials, the C&D debris effects could be evaluated and correlated.

5.2.2 Resilient Modulus Testing

As with any database, the more tests available to compare data, the more evaluations and conclusions can be made on the data and sources of variation. Additional testing of coarse-grained materials that are currently used in the region would provide valuable data sets for future research. Additionally, in order to further evaluate the affects of brick and wood on resilient modulus, more

M_R testing should be conducted on the ERRCO samples. As the company is very willing to donate samples, a large number of tests could be conducted on the ERRCO material, with more detail spent on looking into the effects of wood and brick by percent, on the C&D debris strength.

5.2.3 Alternate Testing

At 25% variation, repeatability of the M_R test is obviously a concern. Other types of triaxial tests could be performed on the same material to determine if the same effects and variations are present. In addition to other triaxial tests, the same M_R test could be performed but at different stress combinations based on local field data.

5.2.4 Confirmation Field Testing

Although actual road testing was not in the purview of this testing, it would allow for possible confirmation of the MEPDG to model roadway use. As the State of Maine has roadway projects built with the seven DOT natural samples, it would be possible to evaluate the performance of some materials in use and compare them to MEPDG predictions. Using this methodology, it could confirm or deny the use of C&D debris provided the MEPDG accurately predicted the Maine test sections and further suggested that a C&D debris material was viable. Despite each roadway having different characteristics, this would be a very valuable resource to understanding the difference between natural materials and C&D debris potential.

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APPENDICES

APPENDIX A: Resilient Modulus Startup Checklist

Resilient Modulus Test Checklist

Technician Name: ______________________________

Technician Signature: ______________________________

Date of Test: ______________________________

- □ Confirm everything is clean
  - □ Double-check O-ring seal grooves
- □ Weigh Membrane

Weight of Membrane	

- □ Lubricate the base using WD-40
- □ Apply vacuum grease to bottom platen
- □ Insert membrane on bottom platen
  - o Install one large O-ring on bottom platen
  - o Install one small O-ring on bottom platen
- □ Install vacuum mold and ensure proper placement of front & back pieces
  - o Install and tighten bottom clamp ring (place 1/3 up from bottom)
  - o Install and tighten upper clamp ring (place 1/3 down from top)

  Note: Ensure even tightening of clamp rings
- □ Apply vacuum grease to top of mold
- □ Reverse membrane onto upper lip of mold
  - o Install one large O-ring on upper lip of mold
  - o Install one small O-ring on upper lip of mold
- □ Apply vacuum to membrane

  Note: Use house vacuum line
- □ Ensure free-draining sample
- □ Prepare vibratory hammer
- □ Take moisture content sample twice

  Note: Mark code on side of weight boat
  - o Weigh containers
  - o Obtain weight boat samples
  - o Place in oven

Code	W_C	W_W	W_D	W%

- ☐ Weigh sample bucket
  Note: Weigh with vibratory hammer bit, scoop, soil and membrane (without cover)

Weight of Sample-Before	

- ☐ Prepare sample with 5 lifts
  Note: 10 lb. Proctor Hammer = 25 blows/layer
  or
  Prepare sample with 10 lifts
  Note: Vibratory Hammer = 15 seconds/layer (do not adjust speed)
- ☐ Reweigh bucket, scoop, soil, and vibratory hammer bit

Weight of Sample-After	
Weight of Specimen (W_{Before}-W_{After})	

- ☐ Level top of sample with stainless steel upper platen
- ☐ Place porous top platen on leveled sample
- ☐ Remove debris from O-ring channel
- ☐ Install top of chamber and load rod
- ☐ Connect vacuum tube to upper platen
- ☐ Apply vacuum grease to upper platen
- ☐ Invert membrane on upper platen
- ☐ Apply vacuum to membrane
- ☐ Carefully remove specimen mold
- ☐ Check membrane for holes
- ☐ Apply latex membrane to holes (if needed)
- ☐ Apply high vacuum grease to O-ring groove
- ☐ Record height of specimen

Height of Specimen	

- ☐ Install chamber wall
- ☐ Apply high vacuum grease to top of chamber walls
- ☐ Install upper chamber locking ring
- ☐ Install top locking ring
- ☐ Move specimen in line with axial load shaft
- ☐ Tighten chamber locking nuts
- ☐ Install LVDTs
  - ☐ Connect LVDT wires
  - ☐ Confirm LVDT inputs

- ☐ Process: System\Inputs\Analog\LVDT 1\Edit
- ☐ Displacement 0.25 #3
- ☐ Check displacement 0.25 #4 as LVDT 2
- ☐ Confirm LVDT height

- ☐ Establish confining pressure
  - ☐ Open supply valve
  - ☐ Open air pressure valve
  - ☐ Zero-out to current air pressure
  - ☐ Connect to chamber valve
  - ☐ Open chamber valve
  - ☐ Confirm top chamber valve is closed
  - ☐ Apply 68.9 kPa of pressure
- ☐ Establish deviator stress
  - ☐ Zero-out axial load cell
  - ☐ Apply 50 N of stress
- ☐ Remove vacuum from specimen
- ☐ Establish free-draining specimen
- ☐ Execute resilient modulus test
- ☐ Upon completion of test, take moisture content sample twice
  Note: Mark code on side of weight boat
  - Weigh containers
  - Obtain weight boat samples
  - Place in oven

Code	W_C	W_W	W_D	**W%**

APPENDIX B: Grain Size Distribution Data

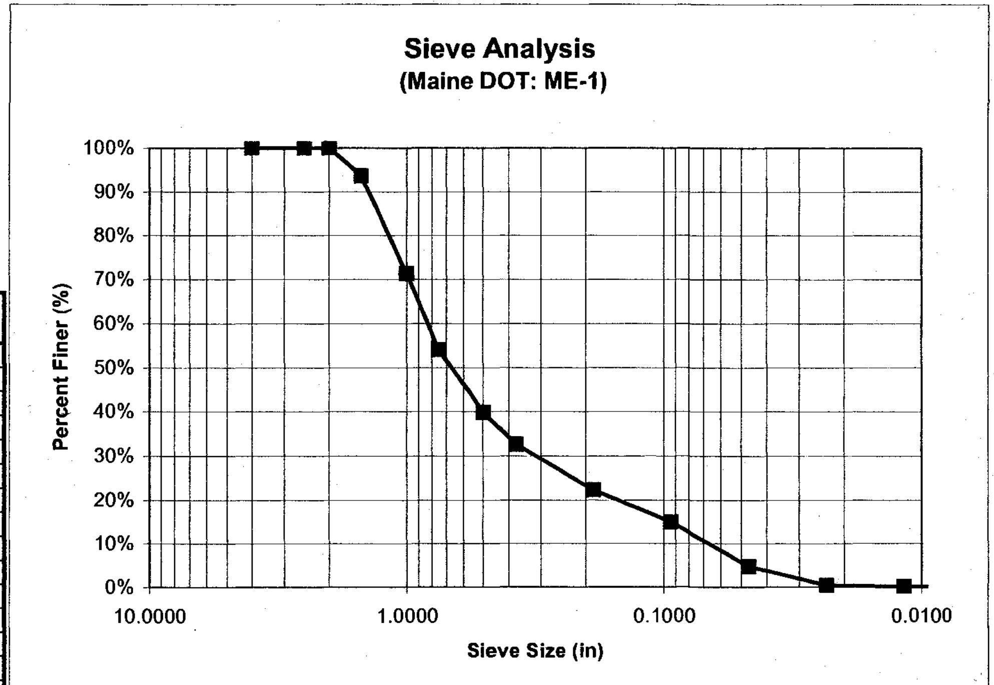
Mark DeRocchi
UNH
C&D Materials Testing (ME-1)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 30 April 2007

Bucket Empty (g):	811.5
Bucket Full (g):	26101.7
Intial Sample (g)	**25290.2**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	0.0	0	0.00%	100.00%
1.5	1.5000	1614.6	1614.6	6.44%	93.56%
1	1.0000	5583.3	7197.9	28.72%	71.28%
3/4	0.7500	4320.4	11518.3	45.96%	54.04%
1/2	0.5000	3592.2	15110.5	60.30%	39.70%
3/8	0.3750	1783.5	16894	67.42%	32.58%
# 4	0.1870	2593.2	19487.2	77.76%	22.24%
# 8	0.0937	1854.7	21341.9	85.16%	14.84%
#16	0.0469	2534.6	23876.5	95.28%	4.72%
# 30	0.0234	1089.4	24965.9	99.63%	0.37%
# 50	0.0117	79.1	25045	99.94%	0.06%
# 100	0.0059	12.9	25057.9	99.99%	0.01%
# 200	0.0029	1.7	25059.6	100.00%	0.00%
Pan	0.0000	0.0	25059.6	100.00%	0.00%

Final Sample (g):	25059.6
Mass Lost (g):	230.6



D60	0.8500
D30	0.3750
D10	0.0703

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
12.09103841	2.353359552

Soil Classification	GW

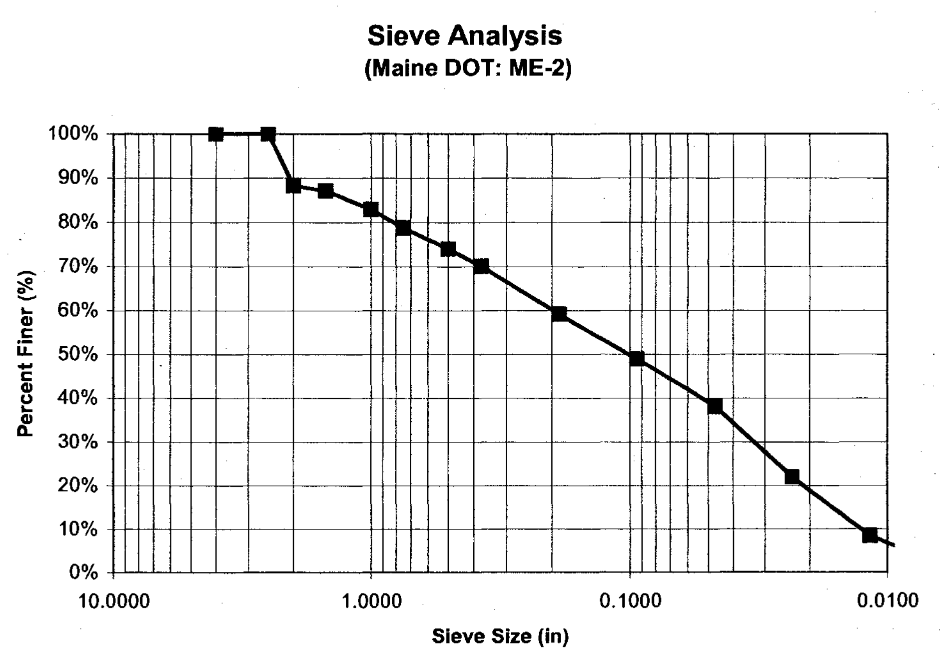
Mark DeRocchi
UNH
C&D Materials Testing (ME-2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 10 May 2007

Bucket Empty (g):	814.1
Bucket Full (g):	29516.6
Intial Sample (g)	**28702.5**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	3350.6	3350.6	11.83%	88.17%
1.5	1.5000	334.5	3685.1	13.01%	86.99%
1	1.0000	1174.4	4859.5	17.15%	82.85%
3/4	0.7500	1174.7	6034.2	21.30%	78.70%
1/2	0.5000	1340.7	7374.9	26.03%	73.97%
3/8	0.3750	1115.7	8490.6	29.97%	70.03%
# 4	0.1870	3095.4	11586	40.89%	59.11%
# 8	0.0937	2907.6	14493.6	51.15%	48.85%
#16	0.0469	3048.1	17541.7	61.91%	38.09%
# 30	0.0234	4581.1	22122.8	78.08%	21.92%
# 50	0.0117	3834.7	25957.5	91.61%	8.39%
# 100	0.0059	2001.8	27959.3	98.68%	1.32%
# 200	0.0029	325.4	28284.7	99.83%	0.17%
Pan	0.0000	49.1	28333.8	100.00%	0.00%

Final Sample (g):	28333.8
Mass Lost (g):	368.7



D60	0.1870
D30	0.0352
D10	0.0119

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
15.71428571	0.555216151

Soil Classification	SP

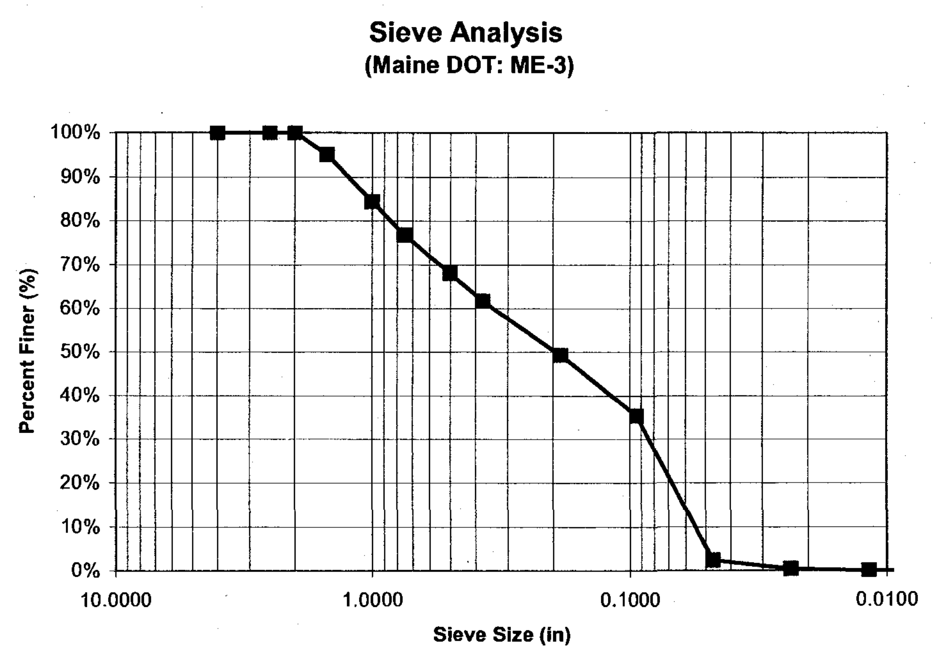
Mark DeRocchi
UNH
C&D Materials Testing (ME-3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 25 April 2007

Bucket Empty (g):	812.3
Bucket Full (g):	25798
Intial Sample (g)	**24985.7**

Sieve No.	Sieve Size (in)	Mass Ret (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0	0	0.00%	100.00%
2 1/2	2.5000	0	0	0.00%	100.00%
2	2.0000	0	0	0.00%	100.00%
1.5	1.5000	1211.9	1211.9	5.00%	95.00%
1	1.0000	2590.8	3802.7	15.69%	84.31%
3/4	0.7500	1837.4	5640.1	23.28%	76.72%
1/2	0.5000	2119.1	7759.2	32.02%	67.98%
3/8	0.3750	1534.5	9293.7	38.36%	61.64%
# 4	0.1870	3023.2	12316.9	50.83%	49.17%
# 8	0.0937	3371	15687.9	64.75%	35.25%
#16	0.0469	7972.6	23660.5	97.65%	2.35%
# 30	0.0234	486.5	24147	99.66%	0.34%
# 50	0.0117	83	24230	100.00%	0.00%
# 100	0.0059	0	24230	100.00%	0.00%
# 200	0.0029	0	24230	100.00%	0.00%
Pan	0.0000	0	24230	100.00%	0.00%

Final Sample (g):	24230
Mass Lost (g):	755.7



D60	0.3750
D30	0.0937
D10	0.0500

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
7.5	0.468250133

Soil Classification	GP

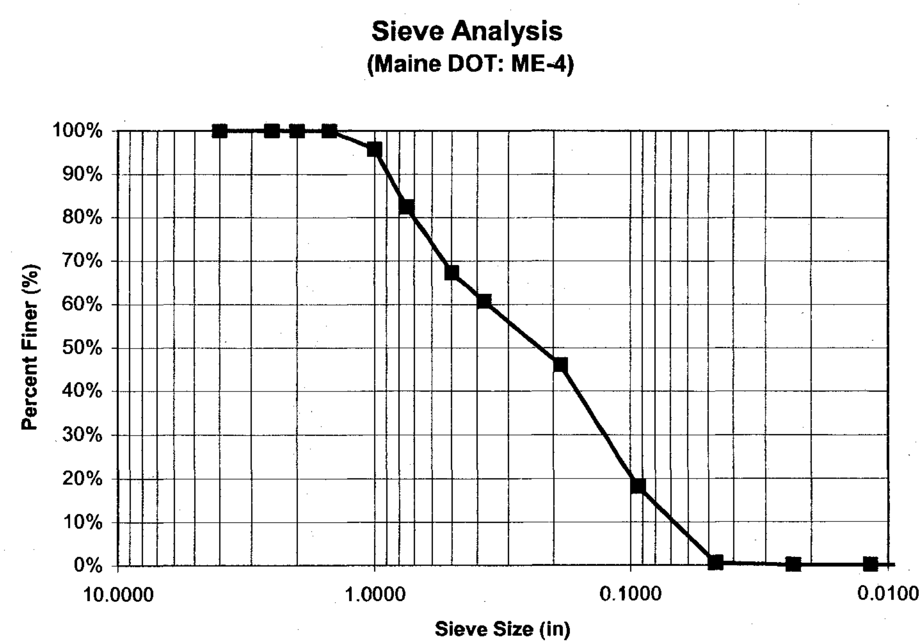
Mark DeRocchi
UNH
C&D Materials Testing (ME-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 2 May 2007

Bucket Empty (g):	815.4
Bucket Full (g):	26097.0
Intial Sample (g)	**25281.6**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	0.0	0	0.00%	100.00%
1.5	1.5000	0.0	0	0.00%	100.00%
1	1.0000	1096.4	1096.4	4.38%	95.62%
3/4	0.7500	3320.2	4416.6	17.63%	82.37%
1/2	0.5000	3804.4	8221	32.82%	67.18%
3/8	0.3750	1638.1	9859.1	39.36%	60.64%
# 4	0.1870	3681.3	13540.4	54.05%	45.95%
# 8	0.0937	6981.7	20522.1	81.93%	18.07%
#16	0.0469	4404.5	24926.6	99.51%	0.49%
# 30	0.0234	119.0	25045.6	99.98%	0.02%
# 50	0.0117	1.4	25047	99.99%	0.01%
# 100	0.0059	1.4	25048.4	100.00%	0.00%
# 200	0.0029	0.9	25049.3	100.00%	0.00%
Pan	0.0000	0.3	25049.6	100.00%	0.00%

Final Sample (g):	25049.6
Mass Lost (g):	232



D60	0.3750
D30	0.1500
D10	0.0650

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
5.769230769	0.923076923

Soil Classification	GP

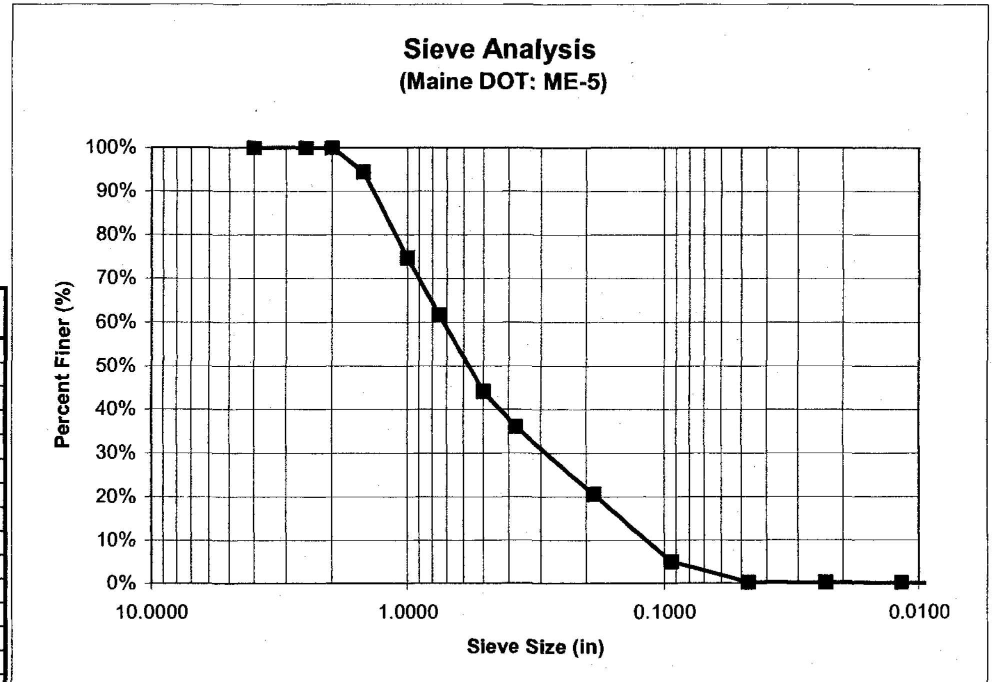
Mark DeRocchi
UNH
C&D Materials Testing (ME-5)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 4 May 2007

Bucket Empty (g):	815.0
Bucket Full (g):	24888.8
Intial Sample (g)	**24073.8**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	0.0	0	0.00%	100.00%
1.5	1.5000	1346.6	1346.6	5.63%	94.37%
1	1.0000	4719.7	6066.3	25.37%	74.63%
3/4	0.7500	3117.0	9183.3	38.41%	61.59%
1/2	0.5000	4210.5	13393.8	56.02%	43.98%
3/8	0.3750	1911.4	15305.2	64.02%	35.98%
# 4	0.1870	3696.4	19001.6	79.48%	20.52%
# 8	0.0937	3731.9	22733.5	95.09%	4.91%
#16	0.0469	1134.8	23868.3	99.83%	0.17%
# 30	0.0234	16.5	23884.8	99.90%	0.10%
# 50	0.0117	17.7	23902.5	99.97%	0.03%
# 100	0.0059	3.1	23905.6	99.99%	0.01%
# 200	0.0029	3.0	23908.6	100.00%	0.00%
Pan	0.0000	0.0	23908.6	100.00%	0.00%

Final Sample (g):	23908.6
Mass Lost (g):	165.2



D60	0.7500
D30	0.3000
D10	0.1250

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
6.00	0.96

Soil Classification	GP

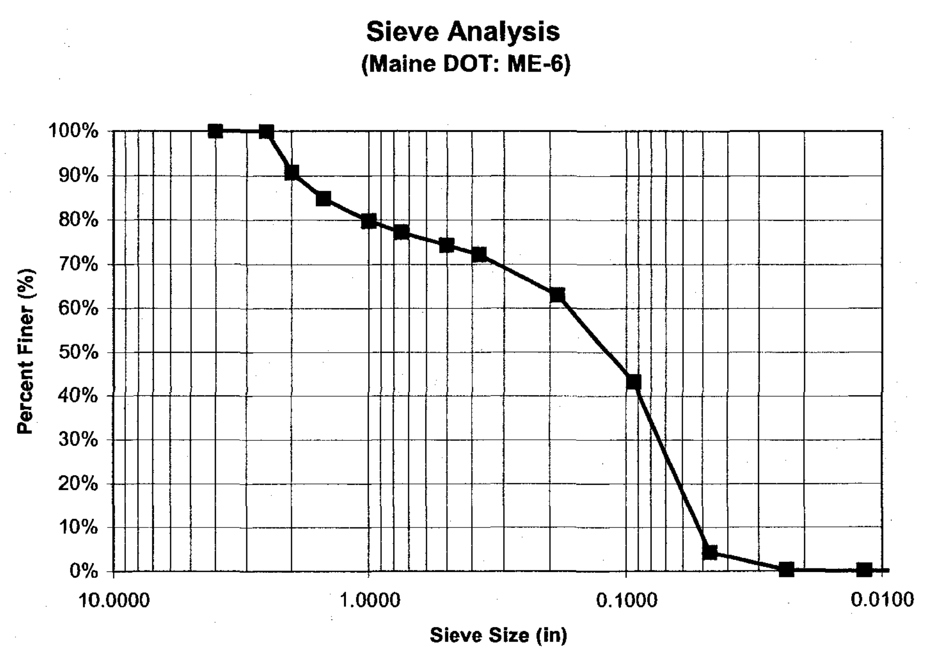
Mark DeRocchi
UNH
C&D Materials Testing (ME-6)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 11 May 2007

Bucket Empty (g):	815.3
Bucket Full (g):	29899.4
Intial Sample (g)	**29084.1**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	2649.4	2649.4	9.34%	90.66%
1.5	1.5000	1642.6	4292	15.14%	84.86%
1	1.0000	1462.0	5754	20.29%	79.71%
3/4	0.7500	715.9	6469.9	22.82%	77.18%
1/2	0.5000	831.3	7301.2	25.75%	74.25%
3/8	0.3750	624.4	7925.6	27.95%	72.05%
# 4	0.1870	2592.7	10518.3	37.09%	62.91%
# 8	0.0937	5593.6	16111.9	56.82%	43.18%
#16	0.0469	11071.4	27183.3	95.86%	4.14%
# 30	0.0234	1117.7	28301	99.80%	0.20%
# 50	0.0117	50.9	28351.9	99.98%	0.02%
# 100	0.0059	3.6	28355.5	99.99%	0.01%
# 200	0.0029	0.7	28356.2	100.00%	0.00%
Pan	0.0000	0.9	28357.1	100.00%	0.00%

Final Sample (g):	28357.1
Mass Lost (g):	727



D60	0.1870
D30	0.0650
D10	0.0234

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
7.991452991	0.96553773

Soil Classification	SP

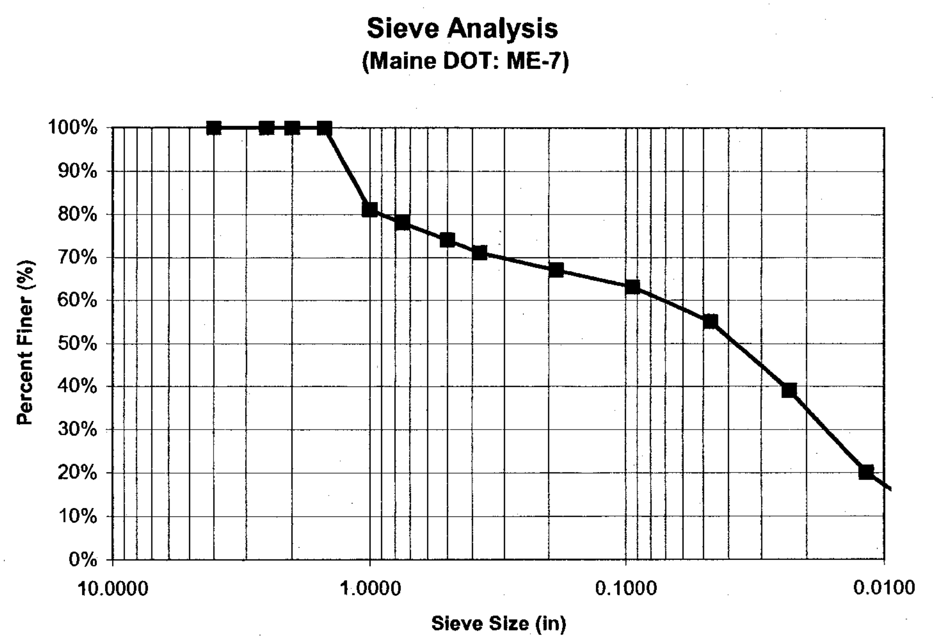
Mark DeRocchi
UNH
C&D Materials Testing (ME-7)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 11 May 2007

Bucket Empty (g):	815.3
Bucket Full (g):	29899.4
Intial Sample (g)	**29084.1**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	0.0	0	0.00%	100.00%
1.5	1.5000	0.0	0	0.00%	100.00%
1	1.0000	4975.0	4975	19.00%	81.00%
3/4	0.7500	825.0	5800	22.00%	78.00%
1/2	0.5000	1395.0	7195	26.00%	74.00%
3/8	0.3750	1050.0	8245	29.00%	71.00%
# 4	0.1870	1258.0	9503	33.00%	67.00%
# 8	0.0937	4100.0	13603	37.00%	63.00%
#16	0.0469	5000.0	18603	45.00%	55.00%
# 30	0.0234	2500.0	21103	61.00%	39.00%
# 50	0.0117	2500.0	23603	80.00%	20.00%
# 100	0.0059	975.0	24578	92.00%	8.00%
# 200	0.0029	945.0	25523	96.50%	3.50%
Pan	0.0000	976.5	26499.5	100.00%	0.00%

Final Sample (g):	26499.5
Mass Lost (g):	2584.6



D60	0.0937
D30	0.0150
D10	0.0060

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
15.61666667	0.400213447

Soil Classification	SP

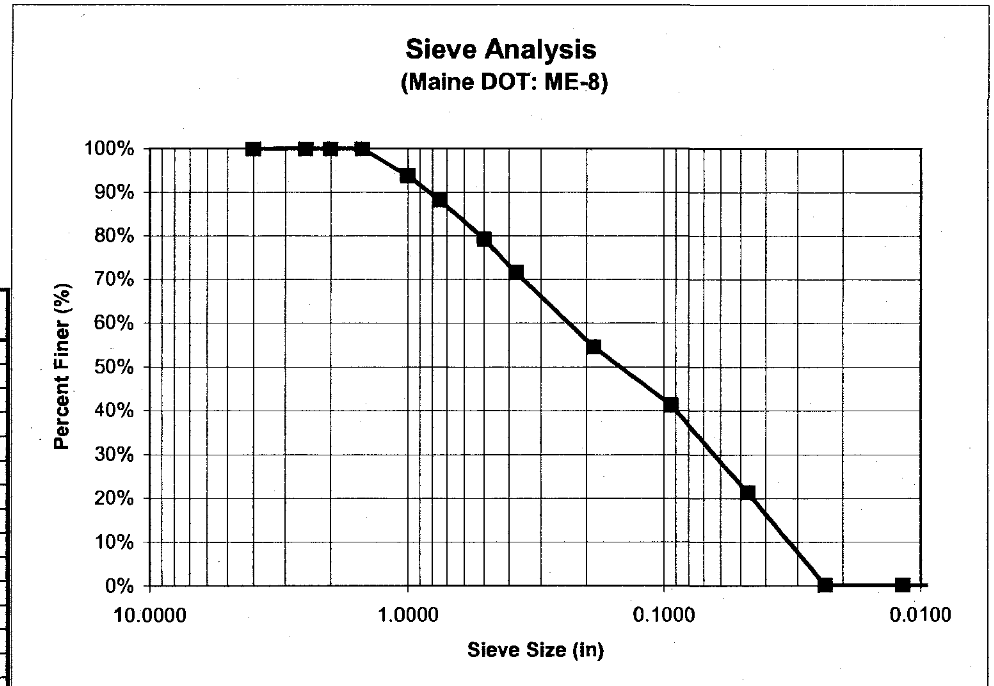
Mark DeRocchi
UNH
C&D Materials Testing (ME-8)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 2 May 2007

Bucket Empty (g):	814.5
Bucket Full (g):	22030.5
Intial Sample (g)	**21216.0**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0	0	0.00%	100.00%
2 1/2	2.5000	0	0	0.00%	100.00%
2	2.0000	0	0	0.00%	100.00%
1.5	1.5000	0	0	0.00%	100.00%
1	1.0000	1314.5	1314.5	6.22%	93.78%
3/4	0.7500	1190.2	2504.7	11.86%	88.14%
1/2	0.5000	1908.9	4413.6	20.89%	79.11%
3/8	0.3750	1618.7	6032.3	28.56%	71.44%
# 4	0.1870	3572.5	9604.8	45.47%	54.53%
# 8	0.0937	2830.2	12435	58.87%	41.13%
#16	0.0469	4197.2	16632.2	78.74%	21.26%
# 30	0.0234	4477.8	21110	99.94%	0.06%
# 50	0.0117	2.1	21112.1	99.95%	0.05%
# 100	0.0059	8.1	21120.2	99.98%	0.02%
# 200	0.0029	3	21123.2	100.00%	0.00%
Pan	0.0000	0.4	21123.6	100.00%	0.00%

Final Sample (g):	21123.6
Mass Lost (g):	92.4



D60	0.2250
D30	0.0625
D10	0.0225

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
10	0.771604938

Soil Classification	SP

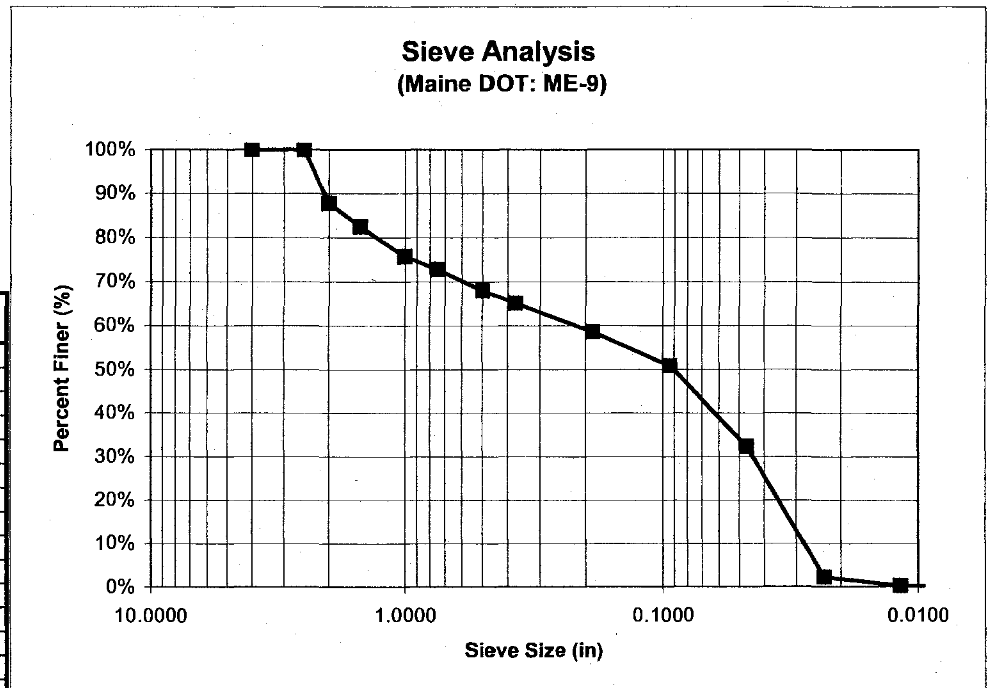
Mark DeRocchi
UNH
C&D Materials Testing (ME-9)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 1 May 2007

Bucket Empty (g):	815.0
Bucket Full (g):	21751.5
Intial Sample (g)	**20936.5**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0.0	0	0.00%	100.00%
2 1/2	2.5000	0.0	0	0.00%	100.00%
2	2.0000	2524.7	2524.7	12.27%	87.73%
1.5	1.5000	1093.7	3618.4	17.58%	82.42%
1	1.0000	1396.1	5014.5	24.36%	75.64%
3/4	0.7500	598.2	5612.7	27.27%	72.73%
1/2	0.5000	984.1	6596.8	32.05%	67.95%
3/8	0.3750	598.9	7195.7	34.96%	65.04%
# 4	0.1870	1341.2	8536.9	41.48%	58.52%
# 8	0.0937	1593.0	10129.9	49.22%	50.78%
#16	0.0469	3781.1	13911	67.59%	32.41%
# 30	0.0234	6217.2	20128.2	97.80%	2.20%
# 50	0.0117	401.7	20529.9	99.75%	0.25%
# 100	0.0059	42.1	20572	99.95%	0.05%
# 200	0.0029	7.7	20579.7	99.99%	0.01%
Pan	0.0000	1.6	20581.3	100.00%	0.00%

Final Sample (g):	20581.3
Mass Lost (g):	355.2



D60	0.1870
D30	0.0469
D10	0.0260

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
7.192307692	0.452408474

Soil Classification	SP

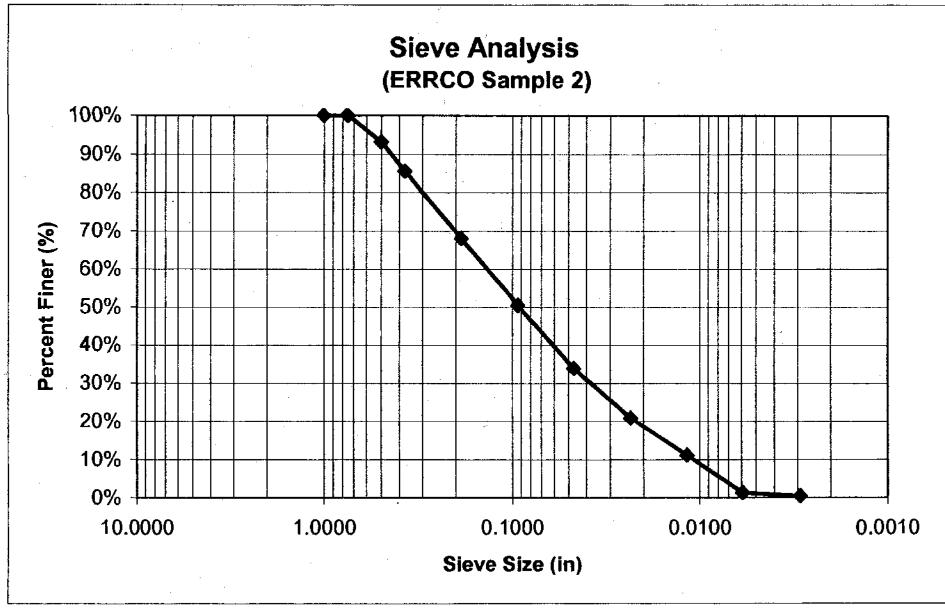
Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 27 Mar 2007

Bucket Empty (g):	820.7
Bucket Full (g):	24979
Intial Sample (g)	**24158.3**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
1	1.0000	0	0	0.00%	100.00%
3/4	0.7500	0	0	0.00%	100.00%
1/2	0.5000	1605.5	1605.5	6.84%	93.16%
3/8	0.3750	1790.7	3396.2	14.46%	85.54%
# 4	0.1870	4117	7513.2	32.00%	68.00%
# 8	0.0937	4133.3	11646.5	49.60%	50.40%
#16	0.0469	3879.7	15526.2	66.12%	33.88%
# 30	0.0234	3071.4	18597.6	79.20%	20.80%
# 50	0.0117	2298.7	20896.3	88.99%	11.01%
# 100	0.0059	2295	23191.3	98.76%	1.24%
# 200	0.0029	187.8	23379.1	99.56%	0.44%
Pan	0	102.3	23481.4	100.00%	0.00%

Final Sample (g):	23481.4
Mass Lost (g):	676.9



D60	0.1404
D30	0.0469
D10	0.0117

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cc)
Cu = D60 / D10	Cc = (D30^2) / (D60 * D10)
11.9957265	1.338514462

Soil Classification	SW

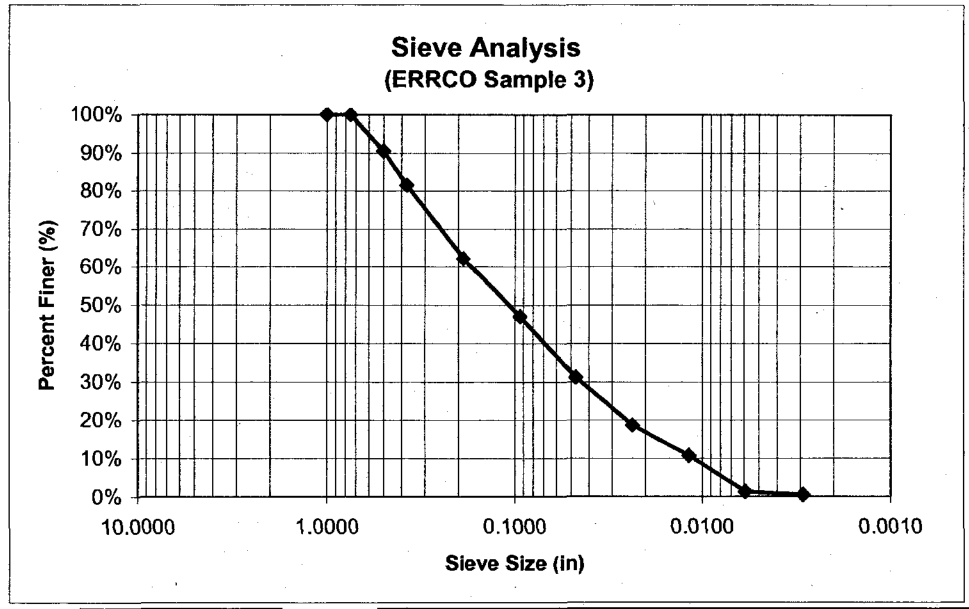
Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 17 Apr 2007

Bucket Empty (g): 820.7
Bucket Full (g): 24979
Intial Sample (g) 24158.3

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
1	1.0000	0	0	0.00%	100.00%
3/4	0.7500	0	0	0.00%	100.00%
1/2	0.5000	2258	2258	9.51%	90.49%
3/8	0.3750	2158	4416	18.60%	81.40%
# 4	0.1870	4585	9001	37.91%	62.09%
# 8	0.0937	3588	12589	53.02%	46.98%
#16	0.0469	3755	16344	68.84%	31.16%
# 30	0.0234	2985	19329	81.41%	18.59%
# 50	0.0117	1887	21216	89.36%	10.64%
# 100	0.0059	2222	23438	98.72%	1.28%
# 200	0.0029	195	23633	99.54%	0.46%
Pan	0	109	23742	100.00%	0.00%

Final Sample (g): 23742
Mass Lost (g): 416.3



D60	0.1870
D30	0.0469
D10	0.0117

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
15.98290598	1.005352164

Soil Classification	SW

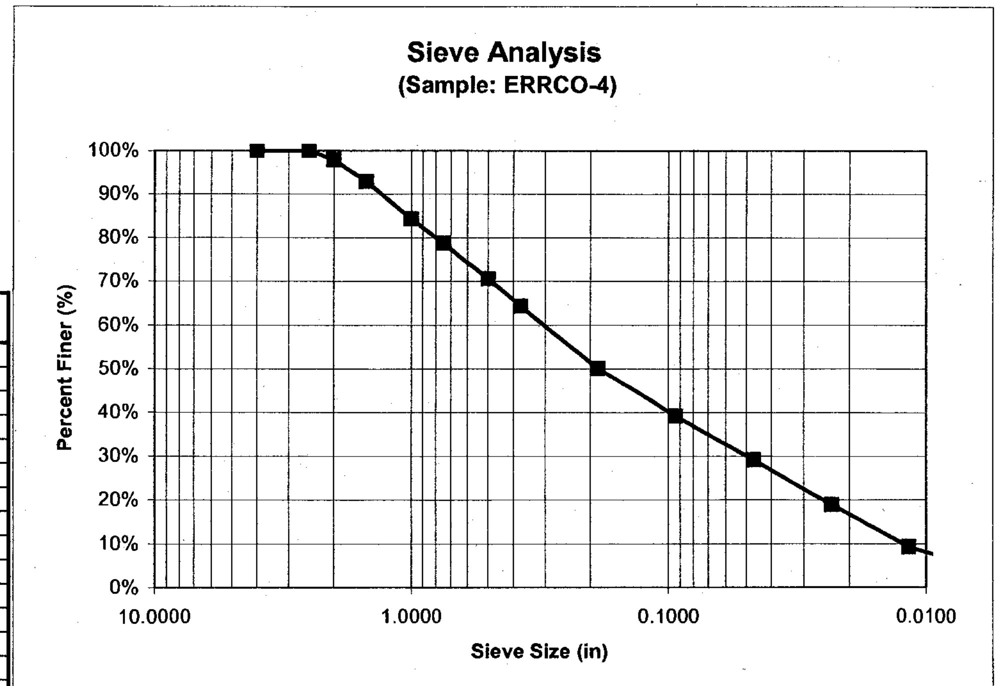
Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO #4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 10-13 July 2007

Bucket Empty (g):	824.4
Bucket Full (g):	25577.1
Intial Sample (g)	**24752.7**

Sieve No.	Sieve Size (in)	Mass Ret. (g)	Cumulative Mass Ret. (g)	Cumulative % Ret	% Passing
4	4.0000	0	0	0.00%	100.00%
2 1/2	2.5000	0	0	0.00%	100.00%
2	2.0000	525.9	525.9	2.15%	97.85%
1.5	1.5000	1218.1	1744	7.14%	92.86%
1	1.0000	2116.6	3860.6	15.80%	84.20%
3/4	0.7500	1356.9	5217.5	21.35%	78.65%
1/2	0.5000	1993.1	7210.6	29.51%	70.49%
3/8	0.3750	1529.7	8740.3	35.77%	64.23%
# 4	0.1870	3471.8	12212.1	49.98%	50.02%
# 8	0.0937	2648.5	14860.6	60.82%	39.18%
#16	0.0469	2454.7	17315.3	70.86%	29.14%
# 30	0.0234	2514.7	19830	81.15%	18.85%
# 50	0.0117	2363.7	22193.7	90.82%	9.18%
# 100	0.0059	1234.6	23428.3	95.88%	4.12%
# 200	0.0029	613.6	24041.9	98.39%	1.61%
Pan	0.0000	393.8	24435.7	100.00%	0.00%

Final Sample (g):	24435.7
Mass Lost (g):	317



D60	0.3750
D30	0.0469
D10	0.0117

Uniformity Coefficient (Cu)	Coefficient of Curvature (Cg)
Cu = D60 / D10	Cg = (D30^2) / (D60 * D10)
32.05128205	0.501335613

Soil Classification	SP

APPENDIX C: Optimum Water Content / Maximum Dry Density Data

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-1)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13-18 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	122.50	120.00	30.40	2.79%
1b	123.20	120.70	30.40	2.77%
2a	147.00	141.80	30.30	4.66%
2b	143.40	138.30	30.70	4.74%
3a	131.10	125.60	31.10	5.82%
3b	135.20	129.20	30.70	6.09%
4a	141.70	134.00	30.30	7.43%
4b	153.10	145.10	30.70	6.99%
5a	151.60	141.90	30.20	8.68%
5b	154.40	145.80	30.40	7.45%
6a				
6b				
7a				
7b				

Sample 1	AVG	**2.78%**
Sample 2	AVG	**4.70%**
Sample 3	AVG	**5.96%**
Sample 4	AVG	**7.21%**
Sample 5	AVG	**8.07%**
Sample 6	AVG	
Sample 7	AVG	

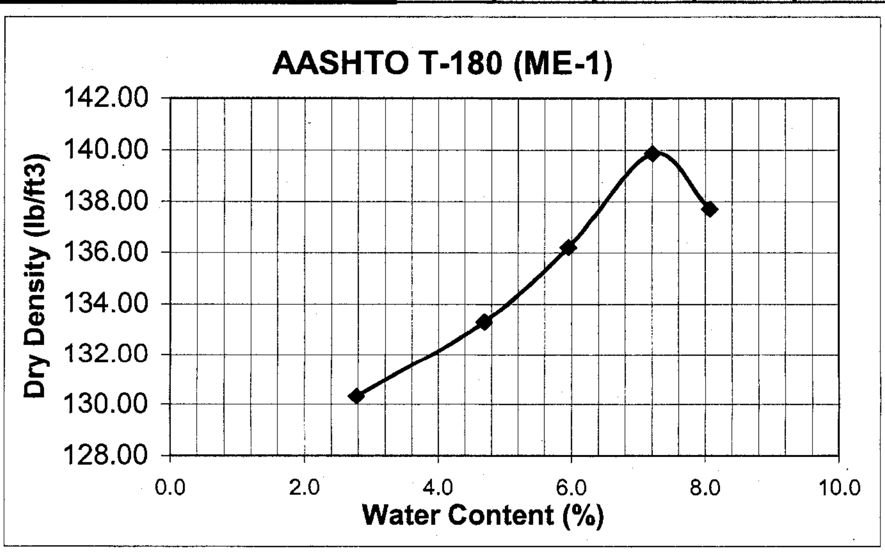
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Vol Mold[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	2.7794	6.2800		4.2570	2145.28	2087.27	133.93	130.30
2	4.7017	6.3650		4.2570	2235.42	2135.03	139.55	133.29
3	5.9557	6.4370		4.2570	2311.77	2181.83	144.32	136.21
4	7.2091	6.5220		4.2570	2401.91	2240.39	149.95	139.86
5	8.0682	6.5050		4.2570	2383.88	2205.90	148.82	137.71
6								
7								



Optimum Water Content = 7.2%
Maximum Dry Density = 140.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-1)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 19-24 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	127.28	124.74	30.40	2.70%
1b	128.01	125.46	30.40	2.68%
2a	152.74	147.40	30.30	4.56%
2b	149.00	143.76	30.70	4.64%
3a	136.22	130.56	31.10	5.69%
3b	140.48	134.30	30.70	5.97%
4a	147.23	139.29	30.30	7.29%
4b	159.08	150.83	30.70	6.87%
5a	157.52	147.50	30.20	8.54%
5b	160.43	151.55	30.40	7.33%
6a				
6b				
7a				
7b				

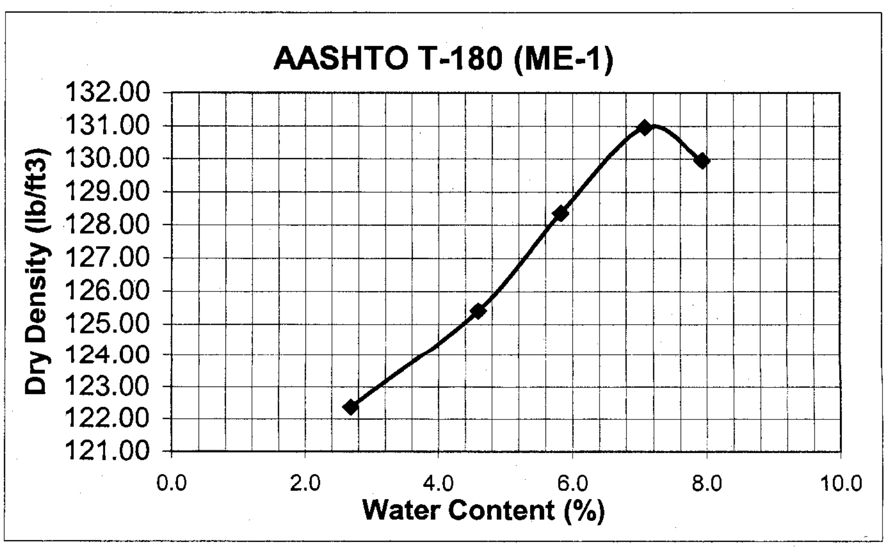
Sample 1	AVG	**2.69%**
Sample 2	AVG	**4.60%**
Sample 3	AVG	**5.83%**
Sample 4	AVG	**7.08%**
Sample 5	AVG	**7.93%**
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Vol Mold[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	2.6902	6.1550		4.2570	2012.75	1960.03	125.65	122.36
2	4.6001	6.2383		4.2570	2101.10	2008.70	131.17	125.40
3	5.8297	6.3089		4.2570	2175.93	2056.07	135.84	128.36
4	7.0796	6.3750		4.2570	2246.02	2097.53	140.21	130.94
5	7.9338	6.3756		4.2570	2246.61	2081.47	140.25	129.94
6								
7								



Optimum Water Content = 7.0%
Maximum Dry Density = 131.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 24-29 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	162.30	157.80	30.50	3.53%
1b	190.70	184.80	30.40	3.82%
2a	175.10	168.50	30.40	4.78%
2b	174.90	168.30	30.70	4.80%
3a	164.90	156.70	30.50	6.50%
3b	186.40	178.10	30.30	5.62%
4a	191.00	179.10	30.50	8.01%
4b	184.60	174.40	30.40	7.08%
5a	199.00	184.20	30.90	9.65%
5b	187.70	174.70	30.40	9.01%
6a				
6b				
7a				
7b				

Sample 1	AVG	**3.68%**
Sample 2	AVG	**4.79%**
Sample 3	AVG	**6.06%**
Sample 4	AVG	**7.55%**
Sample 5	AVG	**9.33%**
Sample 6	AVG	
Sample 7	AVG	

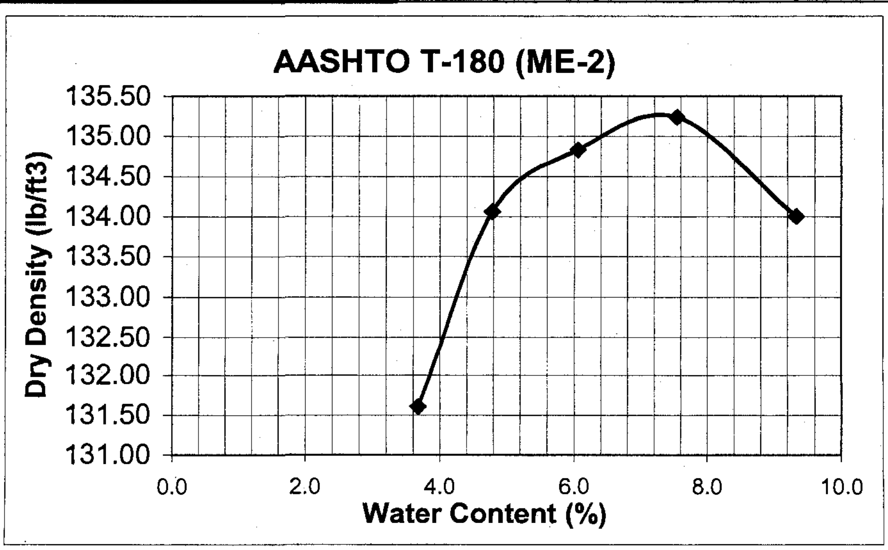
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Vol Mold[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	3.6781	6.3180		4.2570	2185.58	2108.04	136.44	131.60
2	4.7878	6.3790		4.2570	2250.26	2147.45	140.48	134.06
3	6.0567	6.4170		4.2570	2290.56	2159.75	143.00	134.83
4	7.5457	6.4540		4.2570	2329.80	2166.33	145.44	135.24
5	9.3316	6.4700		4.2570	2346.76	2146.46	146.50	134.00
6								
7								



Optimum Water Content = 7.5%
Maximum Dry Density = 135.5 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 12-14 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	165.95	160.96	30.50	3.83%
1b	192.25	188.50	30.40	2.37%
2a	178.74	171.87	30.40	4.86%
2b	178.53	171.67	30.70	4.87%
3a	167.67	159.83	30.50	6.06%
3b	190.56	181.66	30.30	5.88%
4a	193.50	182.68	30.50	7.11%
4b	188.43	177.89	30.40	7.15%
5a	202.98	187.88	30.90	9.62%
5b	191.45	178.19	30.40	8.97%
6a				
6b				
7a				
7b				

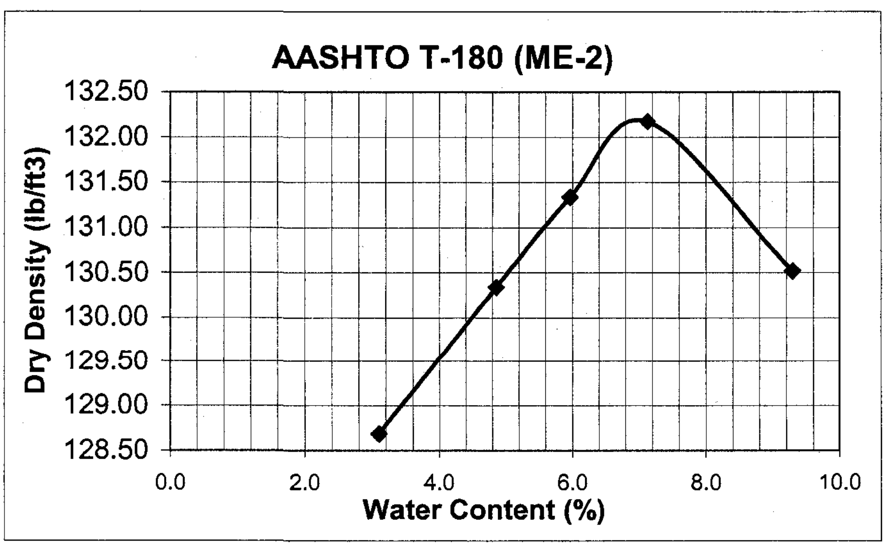
Sample 1	AVG	3.10%
Sample 2	AVG	4.87%
Sample 3	AVG	5.97%
Sample 4	AVG	7.13%
Sample 5	AVG	9.29%
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Vol Mold[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	3.1013	6.2611		4.2570	2125.28	2061.35	132.68	128.69
2	4.8653	6.3216		4.2570	2189.38	2087.80	136.68	130.34
3	5.9682	6.3592		4.2570	2229.32	2103.76	139.17	131.33
4	7.1281	6.3959		4.2570	2268.20	2117.28	141.60	132.18
5	9.2941	6.4118		4.2570	2285.02	2090.70	142.65	130.52
6								
7								



Optimum Water Content = 7.0%
Maximum Dry Density = 132.3 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 20-23 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	163.40	156.30	30.40	5.64%
1b	129.00	124.00	30.40	5.34%
2a	156.00	149.70	30.50	5.29%
2b	150.50	143.70	30.10	5.99%
3a	151.50	144.10	31.20	6.55%
3b	159.30	152.30	30.20	5.73%
4a	159.50	150.40	30.80	7.61%
4b	144.00	136.40	30.60	7.18%
5a				
5b				
6a				
6b				
7a				
7b				

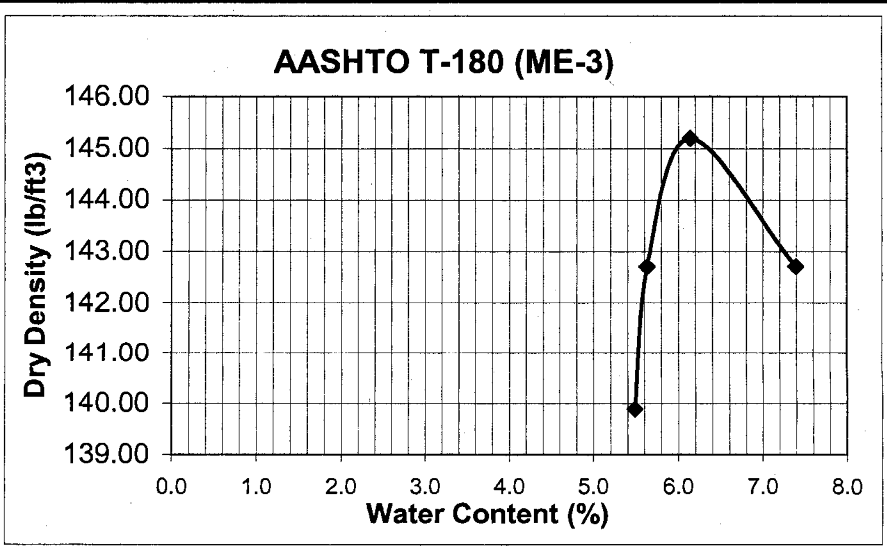
Sample 1	AVG	**5.49%**
Sample 2	AVG	**5.64%**
Sample 3	AVG	**6.14%**
Sample 4	AVG	**7.40%**
Sample 5	AVG	
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.4906	6.4860		4.2570	2363.73	2240.70	147.56	139.88
2	5.6356	6.5340		4.2570	2414.63	2285.81	150.74	142.70
3	6.1437	6.5850		4.2570	2468.72	2325.82	154.12	145.20
4	7.3960	6.5720		4.2570	2454.93	2285.87	153.26	142.70
5								
6								
7								



Optimum Water Content = 6.1%
Maximum Dry Density = 145.25 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 12-13 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	70.50	69.83	30.90	1.72%
1b	88.20	87.09	30.40	1.96%
2a	87.20	85.16	30.50	3.74%
2b	89.80	87.39	30.70	4.25%
3a	126.60	121.90	31.10	5.17%
3b	141.80	136.52	30.70	4.99%
4a	150.70	142.81	30.30	7.01%
4b	167.60	159.76	30.70	6.07%
5a	195.00	182.50	30.40	8.22%
5b	205.00	193.05	30.40	7.35%
6a				
6b				
7a				
7b				

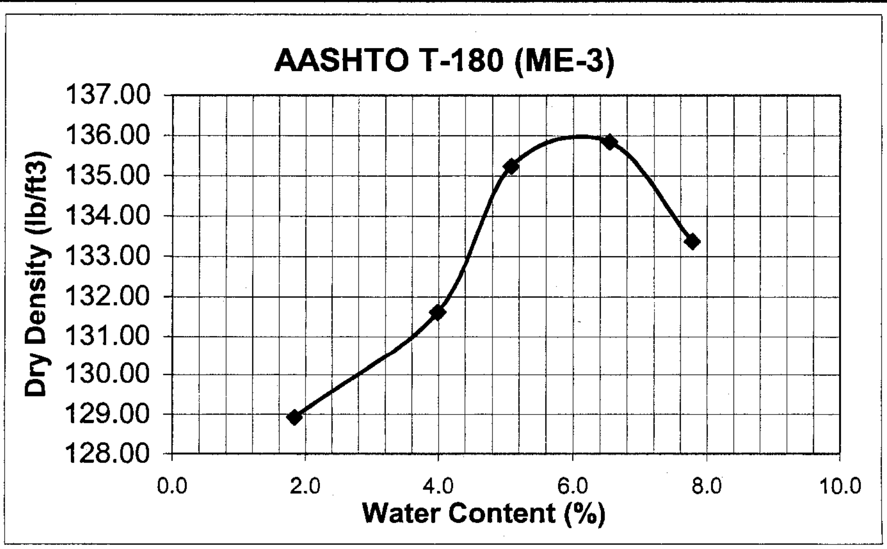
Sample 1	AVG	**1.84%**
Sample 2	AVG	**3.99%**
Sample 3	AVG	**5.08%**
Sample 4	AVG	**6.54%**
Sample 5	AVG	**7.78%**
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	1.8396	6.2432		4.2600	2103.09	2065.10	131.29	128.92
2	3.9917	6.3274		4.2600	2192.34	2108.19	136.86	131.61
3	5.0833	6.4066		4.2600	2276.34	2166.23	142.11	135.23
4	6.5431	6.4462		4.2600	2318.35	2175.97	144.73	135.84
5	7.7827	6.4313		4.2600	2302.60	2136.33	143.75	133.37
6								
7								



Optimum Water Content = 6.0%
Maximum Dry Density = 136.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 9-10 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	164.10	159.90	30.50	3.25%
1b	192.10	187.50	30.40	2.93%
2a	167.80	162.20	30.60	4.26%
2b	189.60	183.30	30.10	4.11%
3a	194.70	187.00	30.70	4.93%
3b	188.20	180.90	31.20	4.88%
4a	187.20	178.40	30.30	5.94%
4b	193.90	185.30	30.70	5.56%
5a	179.20	169.30	30.20	7.12%
5b	211.40	199.90	30.40	6.78%
6a	196.60	185.80	30.50	6.95%
6b	200.60	188.70	30.40	7.52%
7a	186.70	174.90	30.50	8.17%
7b	203.60	191.00	30.30	7.84%

Sample 1	AVG	**3.09%**
Sample 2	AVG	**4.18%**
Sample 3	AVG	**4.90%**
Sample 4	AVG	**5.75%**
Sample 5	AVG	**6.95%**
Sample 6	AVG	**7.24%**
Sample 7	AVG	**8.01%**

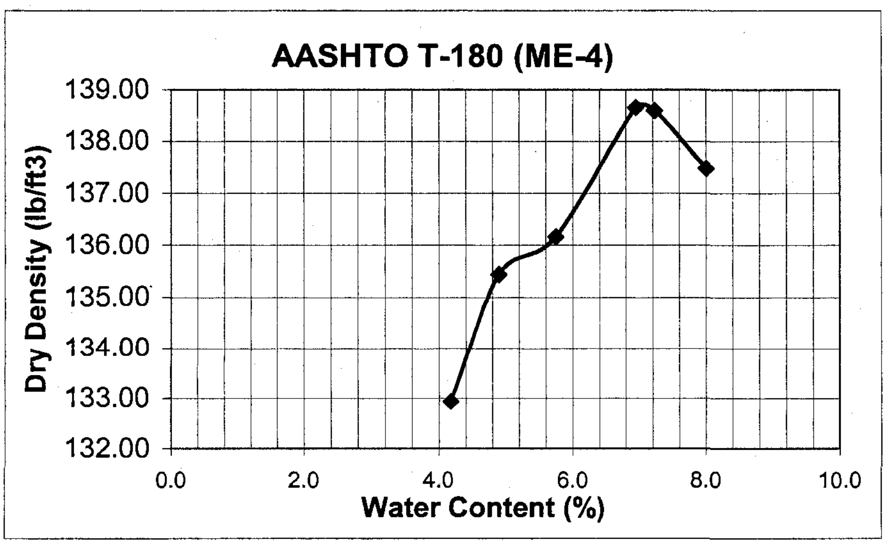
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	3.0869	6.3430		4.2560	2213.15	2146.88	138.16	134.03
2	4.1838	6.3480		4.2560	2218.45	2129.36	138.49	132.93
3	4.9014	6.4020		4.2560	2275.71	2169.38	142.07	135.43
4	5.7523	6.4310		4.2560	2306.47	2181.01	143.99	136.16
5	6.9509	6.4960		4.2560	2375.40	2221.02	148.29	138.65
6	7.2358	6.5010		4.2560	2380.70	2220.06	148.62	138.59
7	8.0062	6.4990		4.2560	2378.58	2202.26	148.49	137.48



Optimum Water Content = 7.0%
Maximum Dry Density = 138.75 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13-14 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	173.80	165.50	30.30	6.14%
1b	173.70	165.40	30.70	6.16%
2a	174.20	165.70	31.00	6.31%
2b	163.90	155.60	30.60	6.64%
3a	194.00	184.00	31.20	6.54%
3b	161.90	152.60	30.70	7.63%
4a	162.40	152.70	30.30	7.92%
4b	178.30	167.20	30.70	8.13%
5a	183.30	171.20	30.20	8.58%
5b	178.20	166.40	30.40	8.68%
6a				
6b				
7a				
7b				

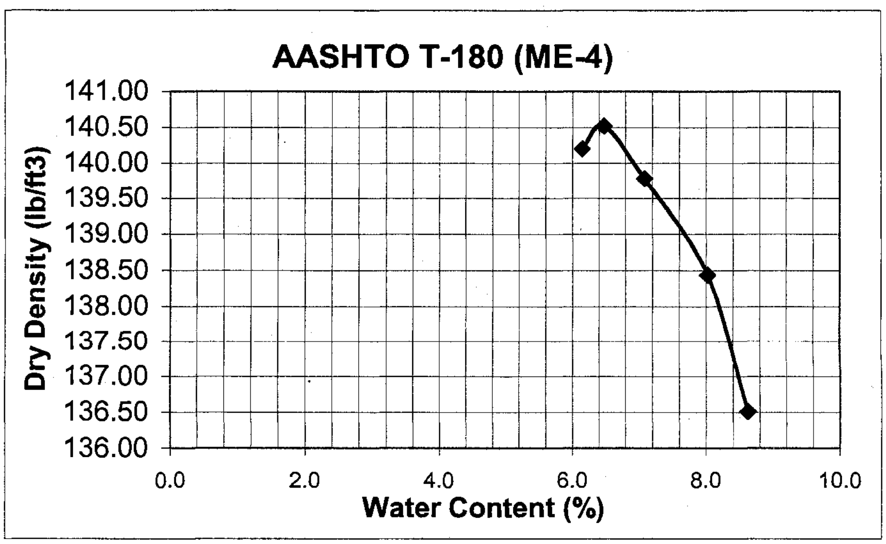
Sample 1	AVG	**6.15%**
Sample 2	AVG	**6.48%**
Sample 3	AVG	**7.09%**
Sample 4	AVG	**8.03%**
Sample 5	AVG	**8.63%**
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	6.1504	6.5030		4.2550	2383.88	2245.76	148.82	140.20
2	6.4752	6.5150		4.2550	2396.61	2250.86	149.62	140.52
3	7.0869	6.5160		4.2550	2397.67	2238.99	149.68	139.78
4	8.0284	6.5140		4.2550	2395.55	2217.52	149.55	138.43
5	8.6290	6.4950		4.2550	2375.40	2186.71	148.29	136.51
6								
7								



Optimum Water Content = 6.5%
Maximum Dry Density = 140.50 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-5)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13-16 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	164.30	161.90	30.90	1.83%
1b	153.10	150.90	30.40	1.83%
2a	157.50	153.10	30.30	3.58%
2b	147.40	143.20	30.70	3.73%
3a	162.40	156.40	31.10	4.79%
3b	161.20	155.50	30.70	4.57%
4a	156.80	148.60	30.30	6.93%
4b	162.20	155.40	30.70	5.45%
5a	151.40	143.80	30.20	6.69%
5b	165.80	157.20	30.40	6.78%
6a	187.40	175.80	30.50	7.98%
6b	168.00	158.70	30.40	7.25%
7a				
7b				

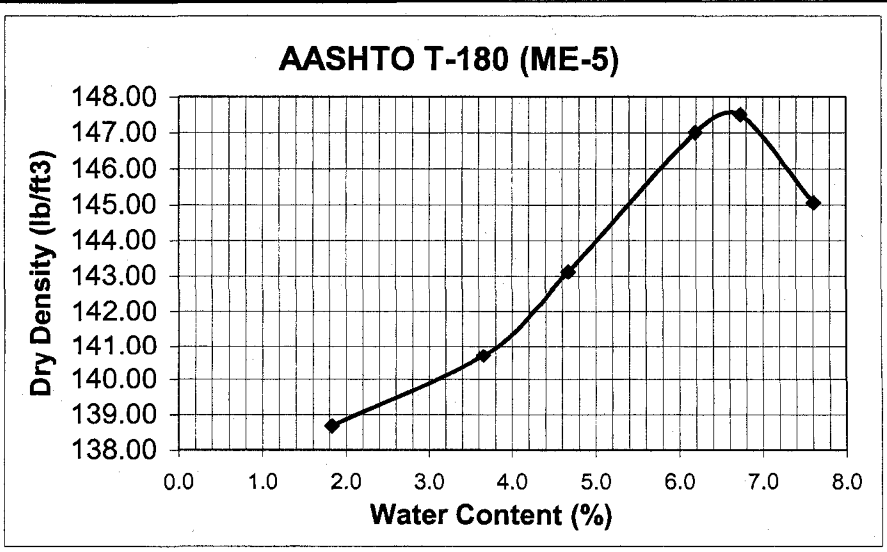
Sample 1	AVG	1.83%
Sample 2	AVG	3.66%
Sample 3	AVG	4.68%
Sample 4	AVG	6.19%
Sample 5	AVG	6.74%
Sample 6	AVG	7.62%
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	1.8289	6.3900		4.2570	2261.93	2221.30	141.21	138.67
2	3.6582	6.4600		4.2570	2336.16	2253.71	145.84	140.69
3	4.6779	6.5200		4.2570	2399.79	2292.54	149.81	143.12
4	6.1923	6.6150		4.2570	2500.53	2354.72	156.10	147.00
5	6.7362	6.6350		4.2570	2521.74	2362.59	157.43	147.49
6	7.6161	6.6150		4.2570	2500.53	2323.57	156.10	145.06
7								



Optimum Water Content = 6.75%
Maximum Dry Density = 147.5 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-5)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 10-12 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	166.85	165.14	30.90	1.27%
1b	155.47	153.92	30.40	1.26%
2a	159.94	156.16	30.30	3.00%
2b	149.68	146.06	30.70	3.14%
3a	164.92	159.53	31.10	4.20%
3b	163.70	158.61	30.70	3.98%
4a	159.23	151.57	30.30	6.32%
4b	164.71	158.51	30.70	4.86%
5a	153.75	146.68	30.20	6.07%
5b	168.37	160.34	30.40	6.18%
6a	190.30	179.32	30.50	7.38%
6b	170.60	161.87	30.40	6.64%
7a				
7b				

Sample 1	AVG	**1.27%**
Sample 2	AVG	**3.07%**
Sample 3	AVG	**4.09%**
Sample 4	AVG	**5.59%**
Sample 5	AVG	**6.12%**
Sample 6	AVG	**7.01%**
Sample 7	AVG	

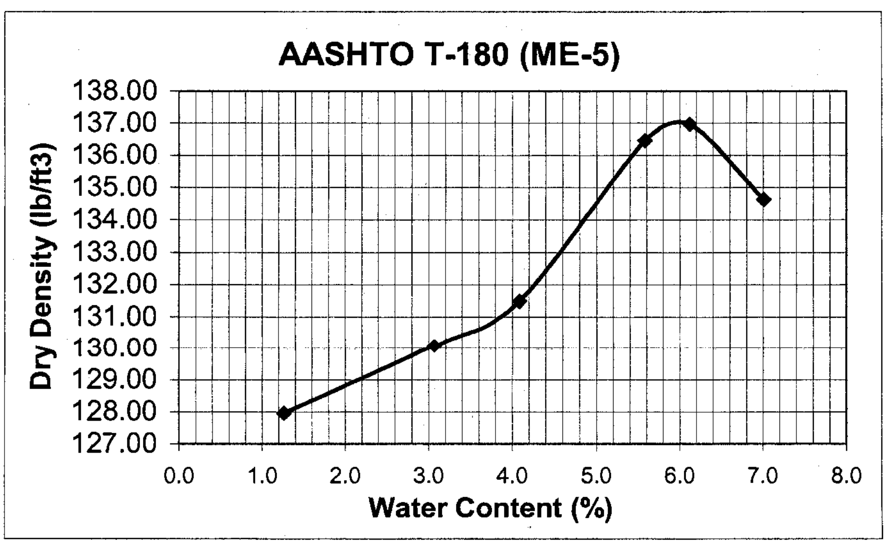
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	1.2659	6.2143		4.2570	2075.58	2049.64	129.57	127.95
2	3.0706	6.2824		4.2570	2147.77	2083.79	134.08	130.09
3	4.0873	6.3244		4.2570	2192.36	2106.27	136.86	131.49
4	5.5854	6.4331		4.2570	2307.62	2185.55	144.06	136.44
5	6.1235	6.4525		4.2570	2328.25	2193.90	145.35	136.96
6	7.0121	6.4331		4.2570	2307.62	2156.41	144.06	134.62
7								



Optimum Water Content = 6.00%
Maximum Dry Density = 137.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-6)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 24-27 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	179.60	170.60	31.10	6.45%
1b	189.50	180.10	30.60	6.29%
2a	188.80	177.60	30.30	7.60%
2b	166.20	156.90	30.70	7.37%
3a	177.00	165.00	31.20	8.97%
3b	177.00	165.90	30.70	8.21%
4a	181.00	168.90	30.50	8.74%
4b	164.60	153.80	30.70	8.77%
5a	187.30	172.20	30.30	10.64%
5b	182.70	169.00	31.00	9.93%
6a				
6b				
7a				
7b				

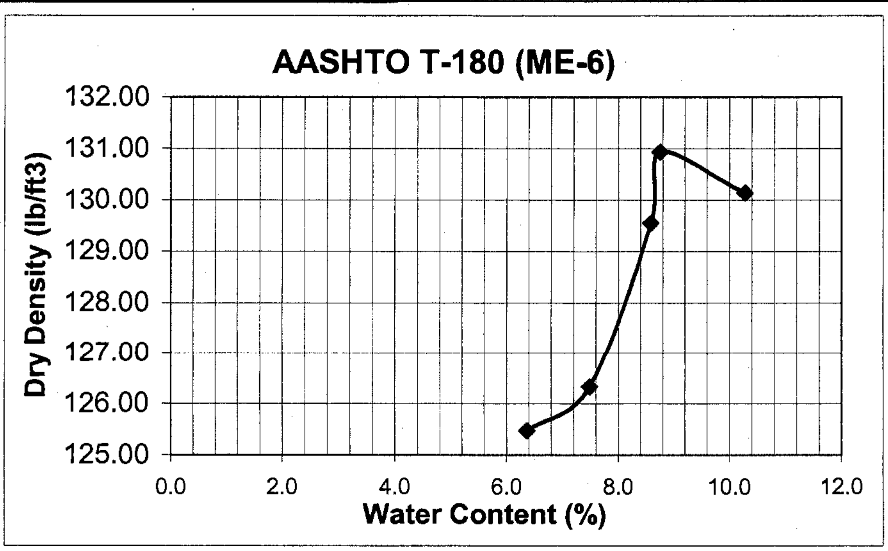
Sample 1	AVG	**6.37%**
Sample 2	AVG	**7.49%**
Sample 3	AVG	**8.59%**
Sample 4	AVG	**8.76%**
Sample 5	AVG	**10.28%**
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	6.3696	6.2730		4.2570	2137.86	2009.84	133.46	125.47
2	7.4864	6.3080		4.2570	2174.97	2023.49	135.78	126.32
3	8.5893	6.3820		4.2570	2253.45	2075.20	140.68	129.55
4	8.7581	6.4080		4.2570	2281.02	2097.33	142.40	130.93
5	10.2844	6.4250		4.2570	2299.04	2084.65	143.52	130.14
6								
7								



Optimum Water Content = 8.7%
Maximum Dry Density = 131.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-6)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13-16 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	183.19	175.72	31.10	5.17%
1b	193.29	185.50	30.60	5.03%
2a	192.58	182.93	30.30	6.32%
2b	169.52	161.61	30.70	6.05%
3a	180.54	169.95	31.20	7.63%
3b	180.54	170.88	30.70	6.89%
4a	185.53	173.97	30.50	8.06%
4b	168.72	158.41	30.70	8.07%
5a	191.98	177.37	30.30	9.94%
5b	187.27	174.07	31.00	9.22%
6a				
6b				
7a				
7b				

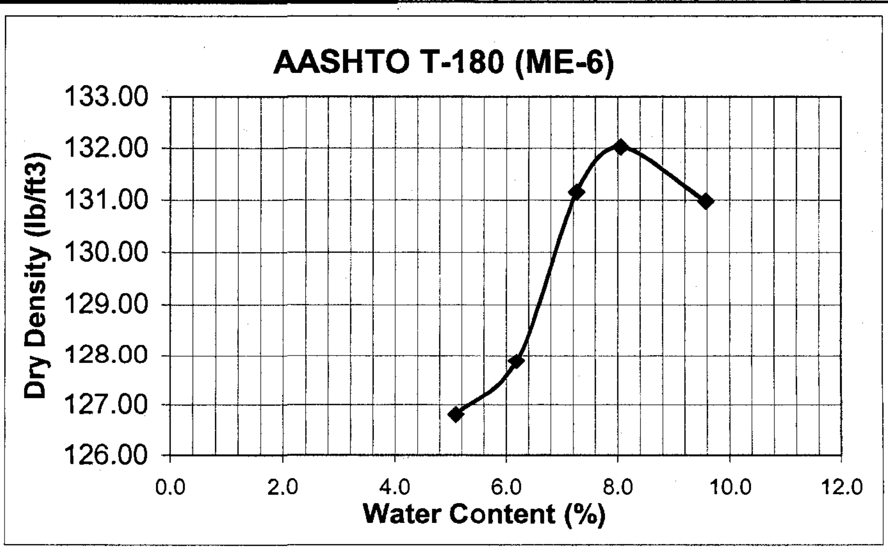
Sample 1	AVG	**5.10%**
Sample 2	AVG	**6.18%**
Sample 3	AVG	**7.26%**
Sample 4	AVG	**8.06%**
Sample 5	AVG	**9.58%**
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.0976	6.2700		4.2570	2134.68	2031.14	133.26	126.80
2	6.1845	6.3080		4.2570	2174.97	2048.30	135.78	127.87
3	7.2629	6.3820		4.2570	2253.45	2100.86	140.68	131.15
4	8.0609	6.4120		4.2570	2285.26	2114.79	142.66	132.02
5	9.5816	6.4250		4.2570	2299.04	2098.02	143.52	130.98
6								
7								



Optimum Water Content = 8.0%
Maximum Dry Density = 132.0 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-7)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 9-10 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	193.60	184.20	31.00	6.14%
1b	183.70	175.40	30.60	5.73%
2a	193.80	182.10	30.30	7.71%
2b	183.10	172.90	30.70	7.17%
3a	196.90	183.10	31.20	9.08%
3b	196.50	184.90	30.70	7.52%
4a	192.20	179.00	30.30	8.88%
4b	199.00	184.30	30.70	9.57%
5a	197.20	182.10	30.20	9.94%
5b	193.80	179.80	30.40	9.37%
6a	214.20	196.90	30.50	10.40%
6b	202.30	186.70	30.40	9.98%
7a				
7b				

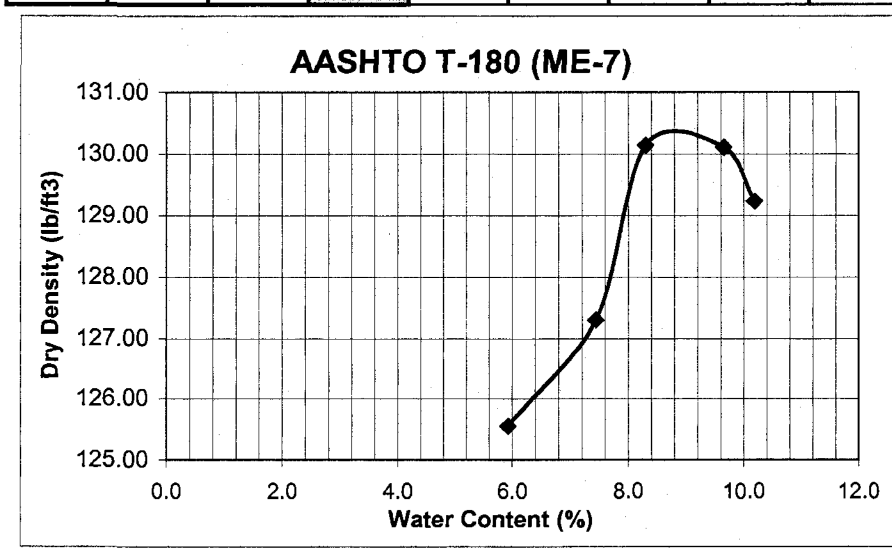
Sample 1	AVG	**5.93%**
Sample 2	AVG	**7.44%**
Sample 3	AVG	**8.30%**
Sample 4	AVG	**9.22%**
Sample 5	AVG	**9.66%**
Sample 6	AVG	**10.19%**
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume [m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.9339	6.2640		4.2550	2130.43	2011.10	133.00	125.55
2	7.4403	6.3210		4.2550	2190.88	2039.16	136.77	127.30
3	8.3038	6.3840		4.2550	2257.69	2084.59	140.94	130.14
4	9.6558	6.4010		4.2550	2275.71	2075.33	142.07	130.10
5	10.1887	6.4100		4.2550	2285.26	2073.95	142.66	129.23
6								
7								



Optimum Water Content = 8.5%
Maximum Dry Density = 130.25 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-7)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 6-8 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	187.79	178.67	31.00	6.17%
1b	178.19	170.14	30.60	5.77%
2a	187.99	176.64	30.30	7.76%
2b	177.61	167.71	30.70	7.22%
3a	190.99	177.61	31.20	9.14%
3b	190.61	179.35	30.70	7.57%
4a	186.43	173.63	30.30	8.93%
4b	193.03	178.77	30.70	9.63%
5a	191.28	176.64	30.20	10.00%
5b	187.99	174.41	30.40	9.43%
6a	207.77	190.99	30.50	10.46%
6b	196.23	181.10	30.40	10.04%
7a				
7b				

Sample 1	AVG	**5.97%**
Sample 2	AVG	**7.49%**
Sample 3	AVG	**8.36%**
Sample 4	AVG	**9.28%**
Sample 5	AVG	**9.72%**
Sample 6	AVG	**10.25%**
Sample 7	AVG	

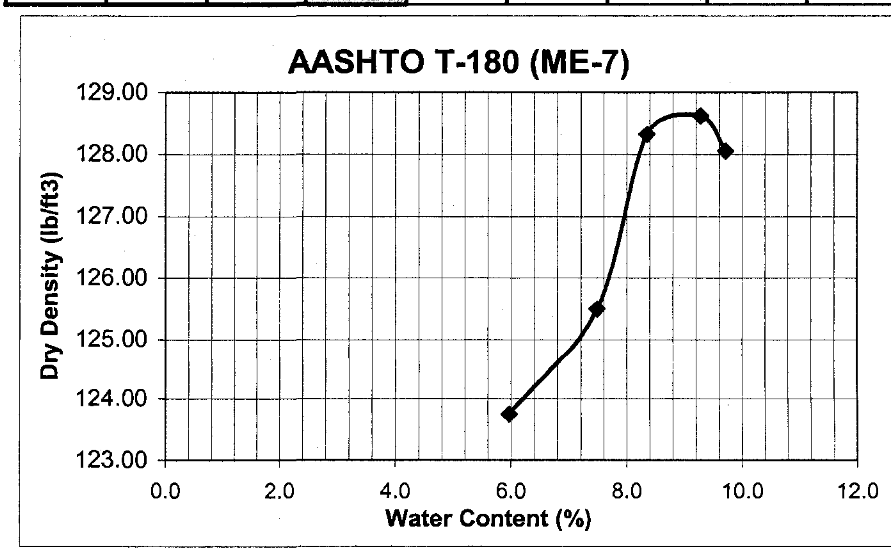
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume [m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.9721	6.2358		4.2550	2100.54	1982.17	131.13	123.74
2	7.4883	6.2926		4.2550	2160.72	2010.19	134.89	125.49
3	8.3562	6.3553		4.2550	2227.22	2055.47	139.04	128.32
4	9.2815	6.3782		4.2550	2251.50	2060.28	140.56	128.62
5	9.7162	6.3772		4.2550	2250.45	2051.15	140.49	128.05
6								
7								



Optimum Water Content = 9.0%
Maximum Dry Density = 128.7 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-8)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 24-29 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	170.10	165.60	31.10	3.35%
1b	185.50	179.90	30.60	3.75%
2a	172.10	164.10	30.70	6.00%
2b	177.40	168.90	30.60	6.15%
3a	181.60	170.00	31.20	8.36%
3b	183.30	173.20	30.70	7.09%
4a	169.50	158.00	30.30	9.01%
4b	178.43	166.40	30.70	8.87%
5a				
5b				
6a				
6b				
7a				
7b				

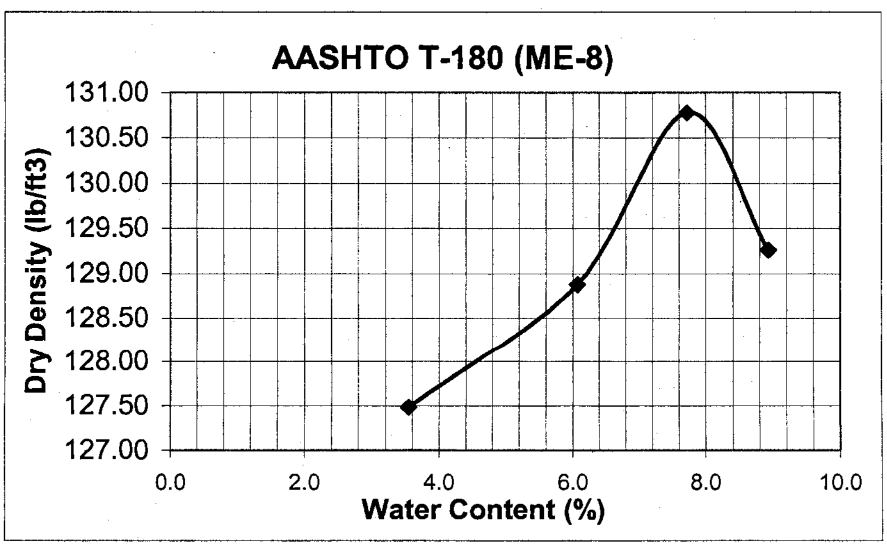
Sample 1	AVG	**3.55%**
Sample 2	AVG	**6.07%**
Sample 3	AVG	**7.72%**
Sample 4	AVG	**8.94%**
Sample 5	AVG	
Sample 6	AVG	
Sample 7	AVG	

AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]
W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	3.5483	6.2510		4.2570	2114.53	2042.07	132.01	127.48
2	6.0715	6.3220		4.2570	2189.82	2064.47	136.71	128.88
3	7.7225	6.3850		4.2570	2256.63	2094.85	140.88	130.78
4	8.9353	6.3840		4.2570	2255.57	2070.56	140.81	129.26
5								
6								
7								



Optimum Water Content = 7.75%
Maximum Dry Density = 130.75 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-8)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 24-29 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	181.90	173.10	30.40	6.17%
1b	172.60	164.50	30.60	6.05%
2a	171.80	161.00	30.60	8.28%
2b	189.10	179.60	30.20	6.36%
3a	170.10	159.00	31.20	8.69%
3b	190.80	179.10	30.20	7.86%
4a	189.60	175.00	30.80	10.12%
4b	178.70	165.80	30.60	9.54%
5a				
5b				
6a				
6b				
7a				
7b				

Sample 1	AVG	**6.11%**
Sample 2	AVG	**7.32%**
Sample 3	AVG	**8.27%**
Sample 4	AVG	**9.83%**
Sample 5	AVG	
Sample 6	AVG	
Sample 7	AVG	

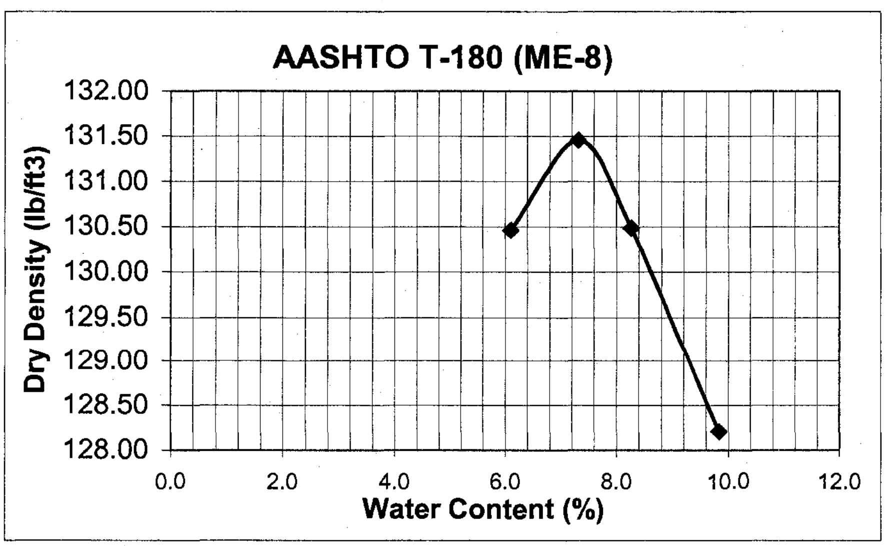
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	6.1080	6.3480		4.2570	2217.39	2089.75	138.43	130.46
2	7.3205	6.3880		4.2570	2259.81	2105.66	141.08	131.45
3	8.2715	6.3910		4.2570	2262.99	2090.11	141.27	130.48
4	9.8331	6.3840		4.2570	2255.57	2053.63	140.81	128.20
5								
6								
7								



Optimum Water Content = 7.5%
Maximum Dry Density = 131.4 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-9)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 20-23 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	149.60	140.00	30.00	8.73%
1b	157.10	146.00	30.60	9.62%
2a	139.10	128.60	30.30	10.68%
2b	163.10	151.00	30.70	10.06%
3a	180.10	165.00	31.10	11.28%
3b	154.90	143.50	30.70	10.11%
4a	171.50	156.00	30.30	12.33%
4b	149.00	137.00	30.70	11.29%
5a				
5b				
6a				
6b				
7a				
7b				

Sample 1	AVG	**9.17%**
Sample 2	AVG	**10.37%**
Sample 3	AVG	**10.69%**
Sample 4	AVG	**11.81%**
Sample 5	AVG	
Sample 6	AVG	
Sample 7	AVG	

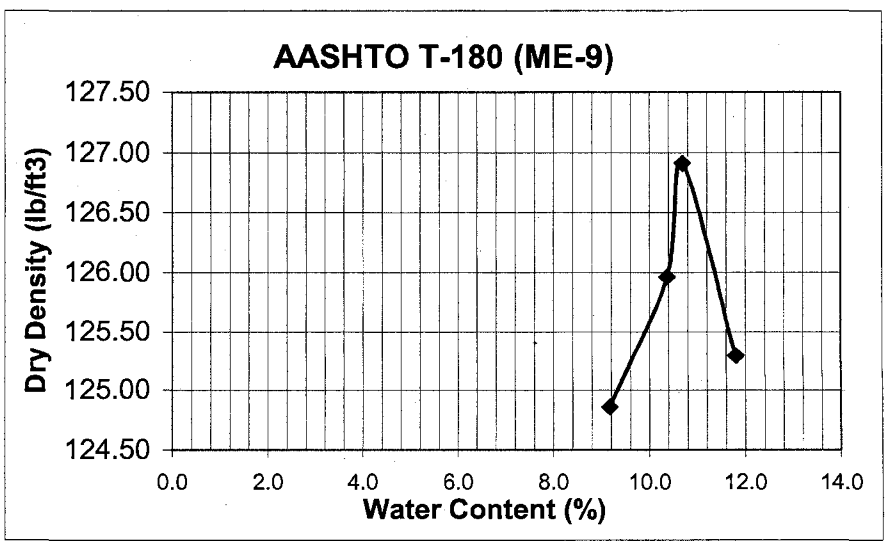
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	9.1730	6.3160		4.2570	2183.46	2000.00	136.31	124.86
2	10.3699	6.3570		4.2570	2226.93	2017.70	139.02	125.96
3	10.6917	6.3790		4.2570	2250.26	2032.91	140.48	126.91
4	11.8099	6.3730		4.2570	2243.90	2006.89	140.08	125.29
5								
6								
7								



Optimum Water Content = 10.7%
Maximum Dry Density = 126.9 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-9)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 24-27 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	164.40	153.80	30.70	8.61%
1b	178.20	167.00	30.50	8.21%
2a	185.00	171.60	31.20	9.54%
2b	163.50	153.00	30.70	8.59%
3a	165.10	152.80	30.30	10.04%
3b	184.30	170.80	30.70	9.64%
4a	197.40	180.80	30.50	11.04%
4b	185.20	171.20	30.30	9.94%
5a	210.70	192.00	31.20	11.63%
5b	186.00	170.50	30.20	11.05%
6a				
6b				
7a				
7b				

Sample 1	AVG	**8.41%**
Sample 2	AVG	**9.06%**
Sample 3	AVG	**9.84%**
Sample 4	AVG	**10.49%**
Sample 5	AVG	**11.34%**
Sample 6	AVG	
Sample 7	AVG	

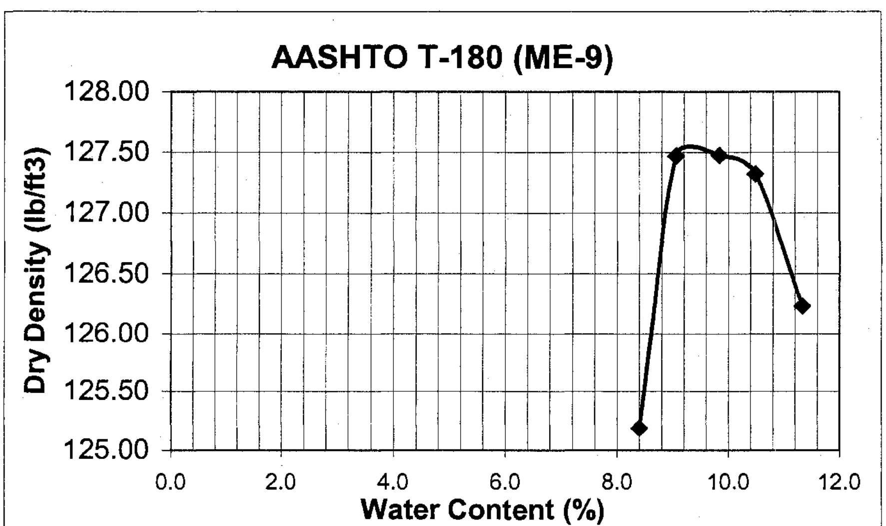
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w(%)	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	8.4080	6.3070		4.2570	2173.91	2005.31	135.71	125.19
2	9.0648	6.3570		4.2570	2226.93	2041.85	139.02	127.47
3	9.8384	6.3720		4.2570	2242.84	2041.95	140.02	127.47
4	10.4904	6.3820		4.2570	2253.45	2039.50	140.68	127.32
5	11.3386	6.3800		4.2570	2251.32	2022.05	140.55	126.23
6								
7								



Optimum Water Content = 9.5%
Maximum Dry Density = 127.75 (lb/ft3)

Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 27 Mar 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	64.88	61.76	2.18	5.24%
1b	64.36	61.10	2.20	5.53%
2a	25.34	22.87	2.14	11.92%
2b	34.37	31.13	2.18	11.19%
3a	38.80	34.64	2.06	12.77%
3b	46.96	41.95	2.09	12.57%
4a	48.66	42.64	2.11	14.85%
4b	47.49	41.69	2.07	14.64%
5a	43.09	37.39	2.18	16.19%
5b	46.56	40.17	2.18	16.82%
6a	66.14	56.29	2.09	18.17%
6b	55.46	47.21	2.10	18.29%

Sample 1	AVG	**5.39%**
Sample 2	AVG	**11.55%**
Sample 3	AVG	**12.67%**
Sample 4	AVG	**14.75%**
Sample 5	AVG	**16.50%**
Sample 6	AVG	**18.23%**

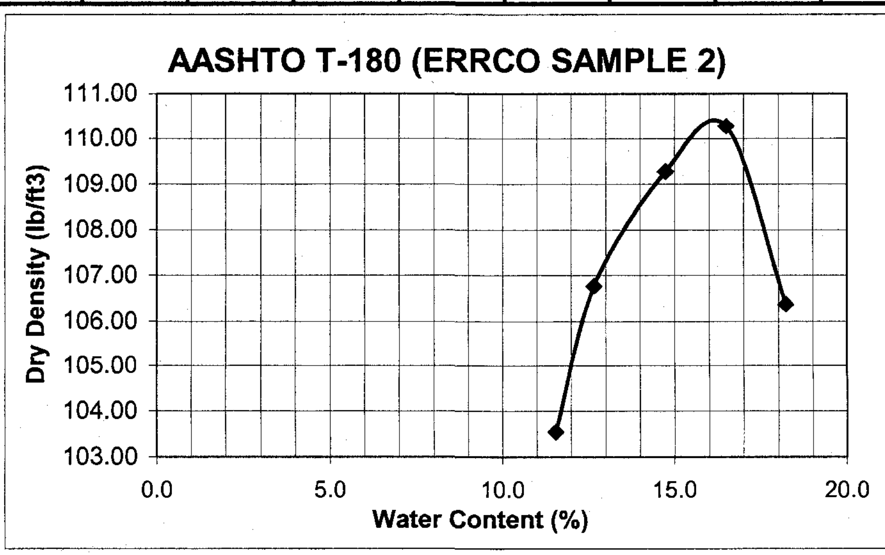
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.3857	5.9511	5.9511	4.2560	1797.56	1705.70	112.22	106.48
2	11.5534	6.0008	5.9511	4.2560	1850.26	1658.64	115.51	103.55
3	12.6688	6.0730	5.9511	4.2560	1926.83	1710.17	120.29	106.76
4	14.7461	6.1500	5.9511	4.2560	2008.48	1750.37	125.39	109.27
5	16.5044	6.1966	5.9511	4.2560	2057.90	1766.37	128.47	110.27
6	18.2310	6.1556	5.9511	4.2560	2014.42	1703.80	125.76	106.36



Optimum Water Content = 16.5%
Maximum Dry Density = 110.5 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO #2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 10-12 June 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	105.40	99.70	31.10	8.31%
1b	85.80	81.70	30.70	8.04%
2a	77.50	72.90	30.30	10.80%
2b	97.60	90.80	30.70	11.31%
3a	100.00	91.10	30.20	14.61%
3b	91.40	83.70	30.40	14.45%
4a	103.80	93.00	30.50	17.28%
4b	104.10	93.50	30.40	16.80%
5a	92.00	82.10	31.00	19.37%
5b	104.30	93.20	30.50	17.70%
6a	93.50	82.60	30.50	20.92%
6b	106.50	94.00	30.30	19.62%
7a	103.50	88.40	30.30	25.99%
7b	93.90	81.60	30.70	24.17%

Sample 1	AVG	**8.17%**
Sample 2	AVG	**11.06%**
Sample 3	AVG	**14.53%**
Sample 4	AVG	**17.04%**
Sample 5	AVG	**18.54%**
Sample 6	AVG	**22.67%**
Sample 7	AVG	**25.08%**

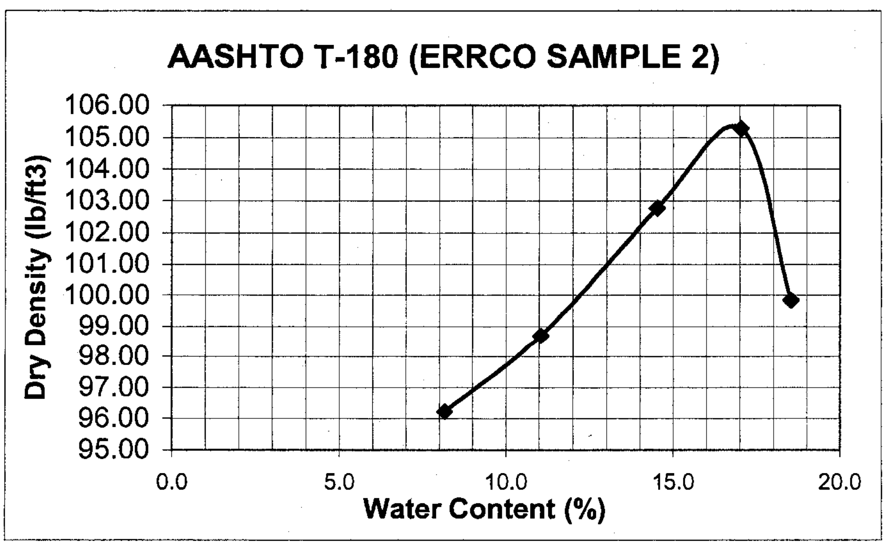
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume [m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	8.1741	5.7722	5.9511	4.2000	1667.23	1541.25	104.08	96.22
2	11.0563	5.8555	5.9511	4.2000	1755.57	1580.79	109.60	98.69
3	14.5303	5.9780	5.9511	4.2000	1885.47	1646.26	117.71	102.77
4	17.0394	6.0613	5.9511	4.2000	1973.81	1686.45	123.22	105.28
5	18.5386	5.9878	5.9511	4.2000	1895.86	1599.36	118.35	99.85
6	22.6748	6.0319	5.9511	4.2000	1942.63	1583.56	121.27	98.86
7	25.0774	5.8898	5.9511	4.2000	1791.94	1432.67	111.87	89.44



Optimum Water Content = 17.0%
Maximum Dry Density = 105.5 (lb/ft3)

Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 17 Apr 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	64.88	61.76	2.18	5.24%
1b	64.36	61.10	2.20	5.53%
2a	25.34	22.87	2.14	11.92%
2b	34.37	31.13	2.18	11.19%
3a	38.80	34.64	2.06	12.77%
3b	46.96	41.95	2.09	12.57%
4a	48.66	42.64	2.11	14.85%
4b	47.49	41.69	2.07	14.64%
5a	43.09	37.39	2.18	16.19%
5b	46.56	40.17	2.18	16.82%
6a	66.14	56.29	2.09	18.17%
6b	55.46	47.21	2.10	18.29%

Sample 1	AVG	**5.39%**
Sample 2	AVG	**11.55%**
Sample 3	AVG	**12.67%**
Sample 4	AVG	**14.75%**
Sample 5	AVG	**16.50%**
Sample 6	AVG	**18.23%**

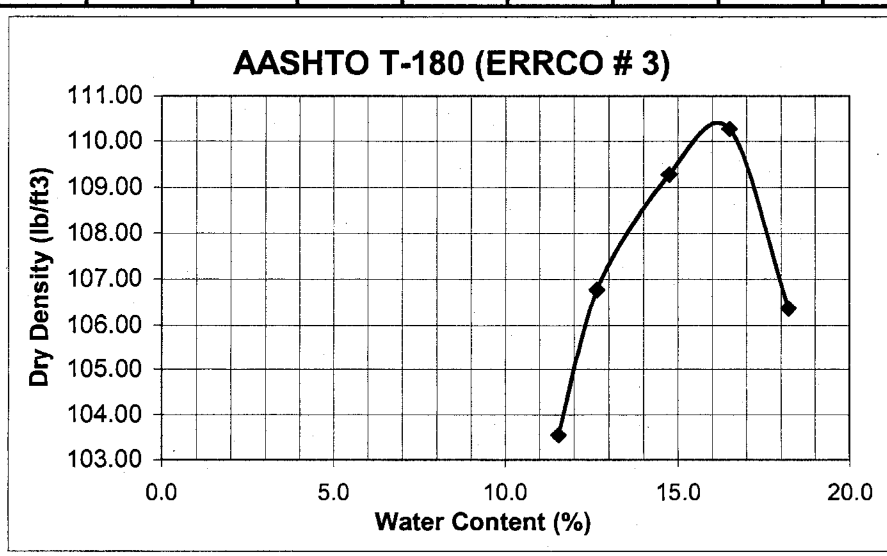
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.3857	5.9511	5.9511	4.2560	1797.56	1705.70	112.22	106.48
2	11.5534	6.0008	5.9511	4.2560	1850.26	1658.64	115.51	103.55
3	12.6688	6.0730	5.9511	4.2560	1926.83	1710.17	120.29	106.76
4	14.7461	6.1500	5.9511	4.2560	2008.48	1750.37	125.39	109.27
5	16.5044	6.1966	5.9511	4.2560	2057.90	1766.37	128.47	110.27
6	18.2310	6.1556	5.9511	4.2560	2014.42	1703.80	125.76	106.36



Optimum Water Content = 16.5%
Maximum Dry Density = 110.5 (lb/ft3)

Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 15 May 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	64.88	61.76	2.18	5.24%
1b	64.36	61.10	2.20	5.53%
2a	24.50	22.87	2.14	7.86%
2b	33.37	31.13	2.18	7.74%
3a	38.80	34.64	2.06	12.77%
3b	46.96	41.95	2.09	12.57%
4a	48.66	42.64	2.11	14.85%
4b	47.49	41.69	2.07	14.64%
5a	43.09	37.39	2.18	16.19%
5b	46.56	40.17	2.18	16.82%
6a	66.14	56.29	2.09	18.17%
6b	55.46	47.21	2.10	18.29%

Sample 1	AVG	**5.39%**
Sample 2	AVG	**7.80%**
Sample 3	AVG	**12.67%**
Sample 4	AVG	**14.75%**
Sample 5	AVG	**16.50%**
Sample 6	AVG	**18.23%**

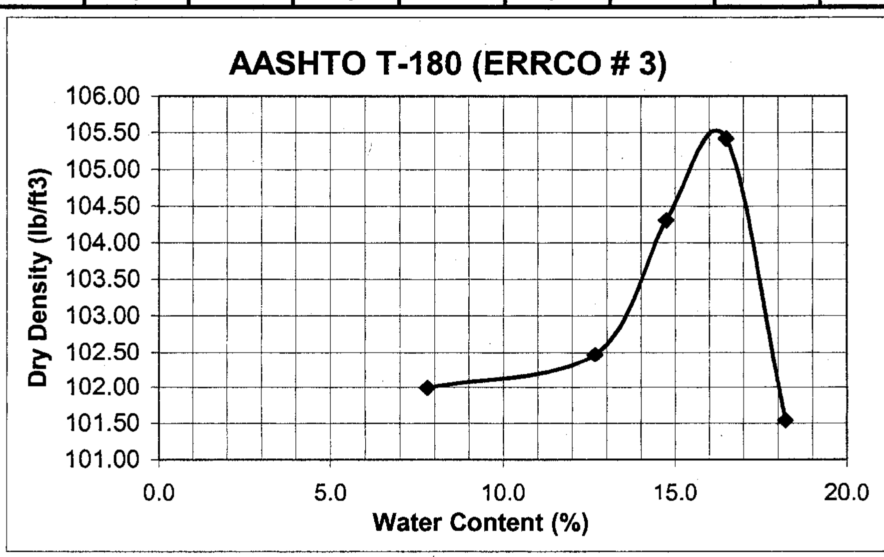
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.3857	5.8678	5.9511	4.2560	1709.21	1621.86	106.70	101.25
2	7.8002	5.9168	5.9511	4.2560	1761.18	1633.74	109.95	101.99
3	12.6688	5.9998	5.9511	4.2560	1849.21	1641.28	115.44	102.46
4	14.7461	6.0639	5.9511	4.2560	1917.18	1670.80	119.69	104.30
5	16.5044	6.1112	5.9511	4.2560	1967.37	1688.66	122.82	105.42
6	18.2310	6.0694	5.9511	4.2560	1923.03	1626.51	120.05	101.54



Optimum Water Content = 17.0%
Maximum Dry Density = 105.5 (lb/ft3)

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO #4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 10-12 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	105.40	99.70	31.10	8.31%
1b	85.80	81.70	30.70	8.04%
2a	77.50	72.90	30.30	10.80%
2b	97.60	90.80	30.70	11.31%
3a	100.00	91.10	30.20	14.61%
3b	91.40	83.70	30.40	14.45%
4a	103.80	93.00	30.50	17.28%
4b	104.10	93.50	30.40	16.80%
5a	92.00	82.10	31.00	19.37%
5b	104.30	93.20	30.50	17.70%
6a	93.50	82.60	30.50	20.92%
6b	106.50	94.00	30.30	19.62%
7a	103.50	88.40	30.30	25.99%
7b	93.90	81.60	30.70	24.17%

Sample 1	AVG	**8.17%**
Sample 2	AVG	**11.06%**
Sample 3	AVG	**14.53%**
Sample 4	AVG	**17.04%**
Sample 5	AVG	**18.54%**
Sample 6	AVG	**22.67%**
Sample 7	AVG	**25.08%**

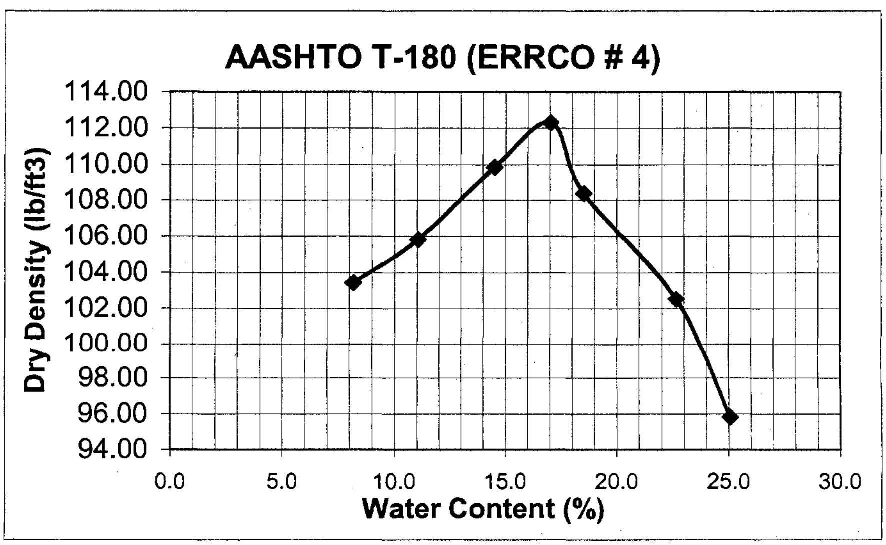
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume [m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	8.1741	5.8900	5.9511	4.2000	1792.15	1656.73	111.88	103.43
2	11.0563	5.9750	5.9511	4.2000	1882.29	1694.90	117.51	105.81
3	14.5303	6.1000	5.9511	4.2000	2014.85	1759.22	125.78	109.82
4	17.0394	6.1850	5.9511	4.2000	2104.98	1798.53	131.41	112.28
5	18.5386	6.1100	5.9511	4.2000	2057.90	1736.06	128.47	108.38
6	22.6748	6.1550	5.9511	4.2000	2014.42	1642.08	125.76	102.51
7	25.0774	6.0100	5.9511	4.2000	1919.41	1534.57	119.82	95.80



Optimum Water Content = 16.5%
Maximum Dry Density = 112.4 (lb/ft3)

Mark DeRocchi
UNH
C&D Materials Testing (ERRCO SAMPLE #4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 16-18 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1a	64.88	61.76	2.18	5.24%
1b	64.36	61.10	2.20	5.53%
2a	25.34	22.87	2.14	11.92%
2b	34.37	31.13	2.18	11.19%
3a	38.80	34.64	2.06	12.77%
3b	46.96	41.95	2.09	12.57%
4a	48.66	42.64	2.11	14.85%
4b	47.49	41.69	2.07	14.64%
5a	43.09	37.39	2.18	16.19%
5b	46.56	40.17	2.18	16.82%
6a	66.14	56.29	2.09	18.17%
6b	55.46	47.21	2.10	18.29%

Sample 1	AVG	**5.39%**
Sample 2	AVG	**11.55%**
Sample 3	AVG	**12.67%**
Sample 4	AVG	**14.75%**
Sample 5	AVG	**16.50%**
Sample 6	AVG	**18.23%**

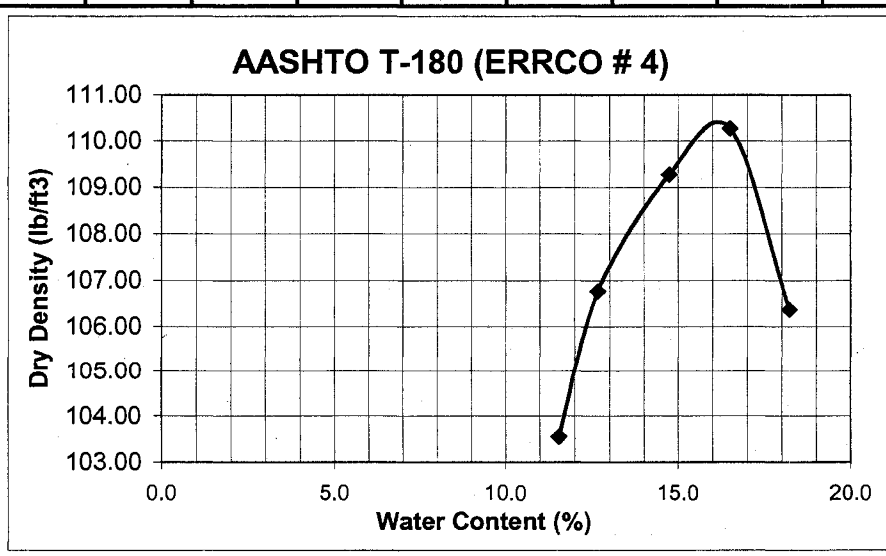
AASHTO T-180 (Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop)
A = mass of container and wet soil
B = mass of container and dry soil
C = mass of container
W = dry density (kg/m3) of soil
W1 = wet density (kg/m3) of soil

W1 = (A-C)*471 [kg/m3]

W = (W1/(w+100))*100

Constant = 1[m3]/Volume[m3]
1[m3]/0.000943[m3]=1060.445

					Metric		English	
Sample	w	A(kg)	B(kg)	C(kg)	W1(kg)	W(kg/m3)	W1(lb/ft3)	W(lb/ft3)
1	5.3857	5.9511	5.9511	4.2560	1797.56	1705.70	112.22	106.48
2	11.5534	6.0008	5.9511	4.2560	1850.26	1658.64	115.51	103.55
3	12.6688	6.0730	5.9511	4.2560	1926.83	1710.17	120.29	106.76
4	14.7461	6.1500	5.9511	4.2560	2008.48	1750.37	125.39	109.27
5	16.5044	6.1966	5.9511	4.2560	2057.90	1766.37	128.47	110.27
6	18.2310	6.1556	5.9511	4.2560	2014.42	1703.80	125.76	106.36



Optimum Water Content = 16.5%
Maximum Dry Density = 110.5 (lb/ft3)

APPENDIX D: California Bearing Ratio Data

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-1)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 27 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	164.20	153.20	30.6	[illegible]
2	179.70	167.50	30.5	[illegible]

Average Moisture Content
8.9387

Height Before (in)	0.4629
Height After (in)	0.4641

Percent Swell	0.02617882

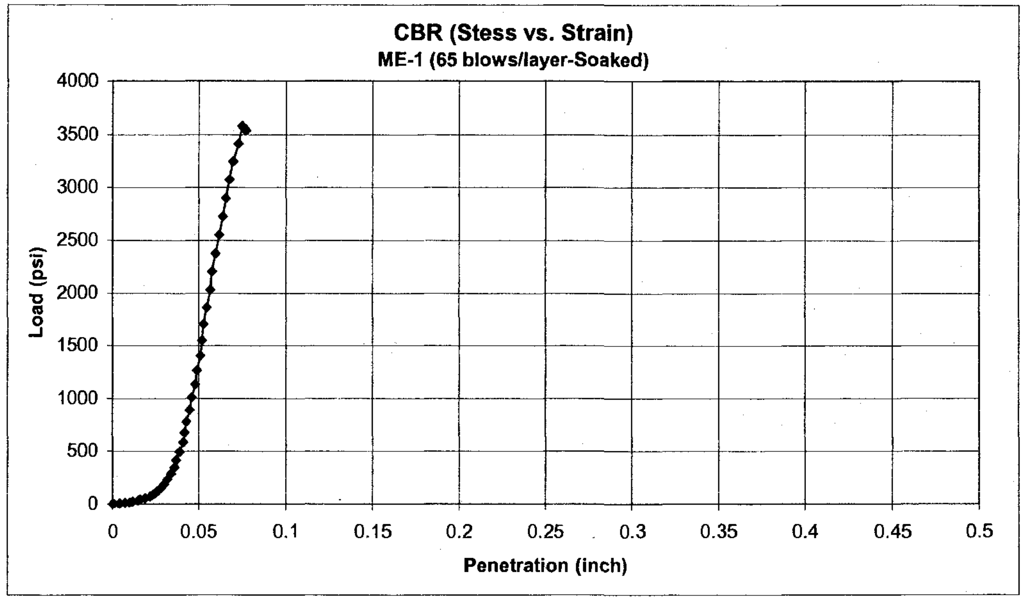
Sample Mass (g)	5151.30
Sample Mass (lb)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	151.4156
Density (Dry) (lb/ft3)	138.9916

AASHTO T-193 (California Bearing Ratio)

Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME--1		
Test:	Triaxial		
Specimen:	ME-1 CBR-S-1		
Number:	3		
Description:	65 Blows/Layer Soaked		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	07/27/07		
Starting Time	10:39:13		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	42		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	10	0.001	2.248089	0.74961287	
9.99994	57	0.004	12.8141073	4.27279336	
14.9999	117	0.007	26.3026413	8.77047059	

Load-1 (psi)	3536.524	Load-2 (psi)	3536.524
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	353.652	CBR (0.2)	235.768

Reported CBR	353.7

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-1)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 7 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	230.70	217.80	30.9	6.9021
2	242.90	230.40	30.7	6.2594

Average Moisture Content
6.5807

Height Before (in)	0.4703
Height After (in)	0.4661

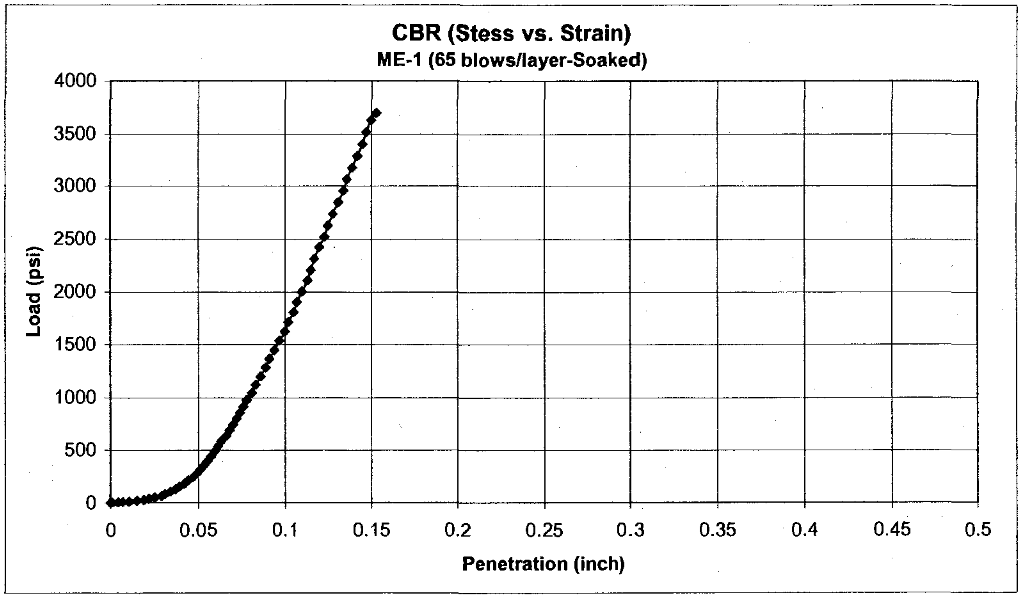
Percent Swell	-0.0905351

[illegible]	5058.10
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	148.7055
Density (Dry) (lb/ft3)	139.5238

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software: GCTS C.A.T Version: 1.82
Project: DeRocchi Tests
Customer: _ERRCO Sample 1
Sample: ME--1
Test: Triaxial
Specimen: ME-1 CBR-S-2
Number: 5
Description: 65 blows/layer Soaked
Container ID _
Type: Rock Soft
Specific Gra 2.7
Height of Pla 0 (mm)
Diametral Me 0 (mm)
Mass of Initia 0 (gr)
Mass of Fina 0 (gr)
Mass of Fina 0 (gr)
Starting Date 7/8/2007
Starting Time 11:36:28
Test Results Stopped by user!
Stages: 1
Stage Index: 1
Type: Universal
Specimen:
Height: 200 (mm)
Axial Gauge 200 (mm)
Diameter: 100 (mm)
Area: 78.54 cm^2
Volume: 1570.8 cm^3
Data Points: 61



Time sec	CBR Axial Lo N	LVDT #1 inch	Axial Load (lb-f)	Axial Load (psi)	Area (sq in)
0.00097637	0	0	0	0	2.999
4.99997	10	0.001	2.248089	0.74961287	
9.99994	37	0.004	8.3179293	2.77356762	
14.9999	77	0.007	17.3102853	5.77201911	

Load-1 (psi)	3172.587	Load-2 (psi)	3172.587
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	317.259	CBR (0.2)	211.506

Reported CBR	317.3

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	170.80	161.60	30.4	[illegible]
2	174.80	164.50	30.7	[illegible]

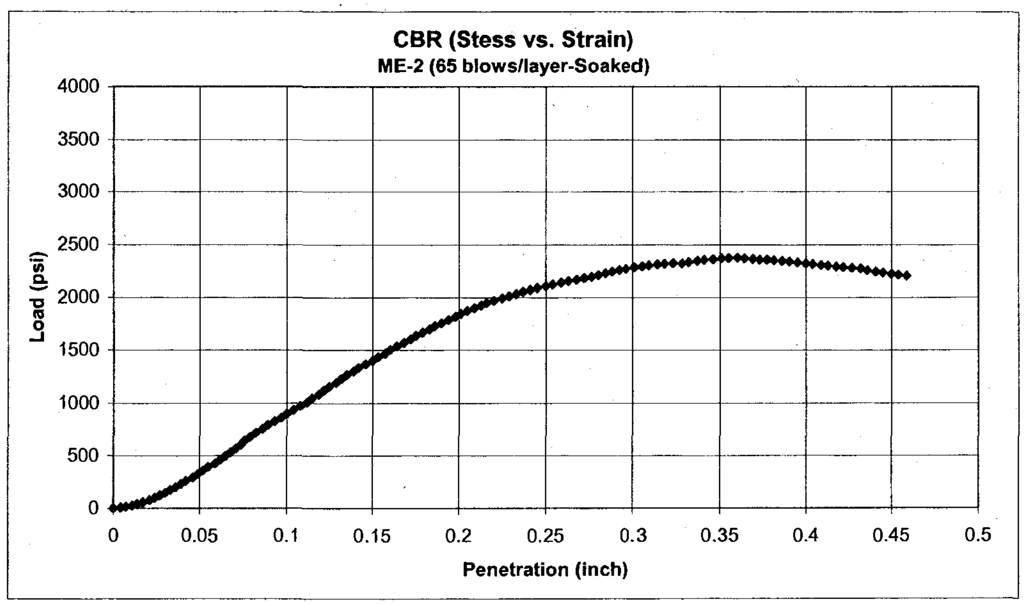
Average Moisture Content
7.2728

Height Before (in)	0.5755
Height After (in)	0.5525
Percent Swell	-0.5017607

Sample Mass (g)	4816.00
Sample Mass (lb)	[illegible]
Volume (ft^3)	[illegible]
Density (Wet) (lb/ft3)	141.5599
Density (Dry) (lb/ft3)	131.9626

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-2		
Test:	Triaxial		
Specimen:	ME-2 CBR-S-1		
Number:	1		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	08/13/07		
Starting Time	10:17:09		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	134		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	0	0	0	0	
9.99994	66	0.004	14.8373874	4.94744495	
14.9999	183	0.007	41.1400287	13.7179155	

Load-1 (psi)	1081.466	Load-2 (psi)	1966.459
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	108.147	CBR (0.2)	131.097

Reported CBR	108.1

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 21 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	160.50	152.40	31.0	[illegible]
2	155.30	147.80	30.6	[illegible]

Average Moisture Content
6.5357

Height Before (in)	0.5021
Height After (in)	0.5041

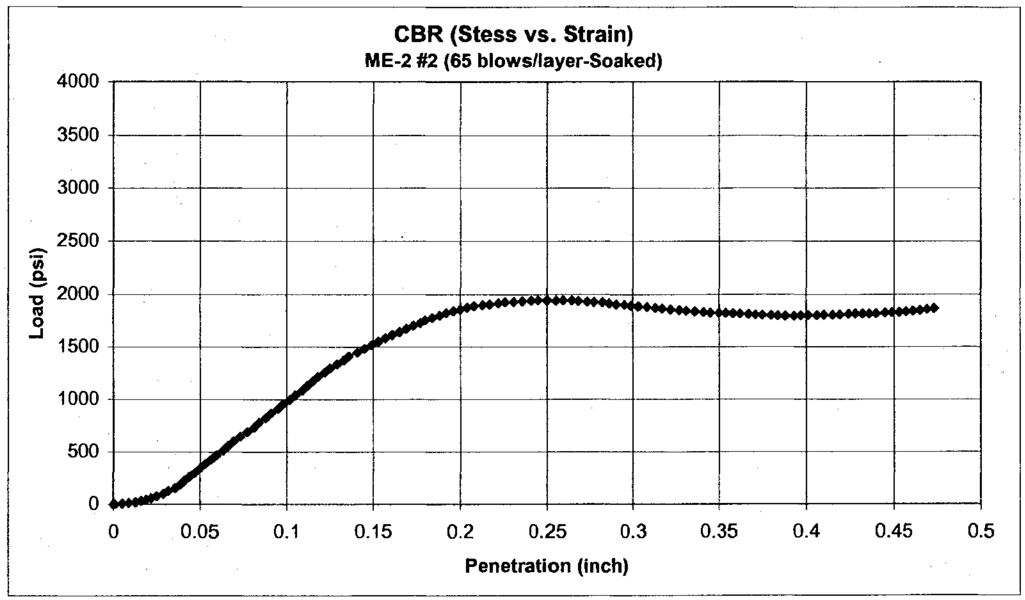
Percent Swell	0.04363137

Sample Mass (g)	[illegible]
Sample Size	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	147.6621
Density (Dry) (lb/ft3)	138.6033

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-2		
Test:	Triaxial		
Specimen:	CBR-S-2		
Number:	4		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0	(mm)	
Diametral Me	0	(mm)	
Mass of Initia	0	(gr)	
Mass of Fina	0	(gr)	
Mass of Fina	0	(gr)	
Starting Date	08/21/07		
Starting Time	14:09:54		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq In)
0.00097637	-4	0	-0.8992356	-0.2998451	2.999
4.99997	17	0.001	3.8217513	1.27434188	
9.99994	90	0.005	20.232801	6.74651584	
14.9999	159	0.009	35.7446151	11.9188446	

Load-1 (psi)	1208.301	Load-2 (psi)	1902.068
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	120.830	CBR (0.2)	126.805

Reported CBR	120.8

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 31 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	147.30	140.50	31.5	[illegible]
2	163.30	156.30	31.4	[illegible]

Average Moisture Content
5.6785

Height Before (in)	0.5321
Height After (in)	0.5322

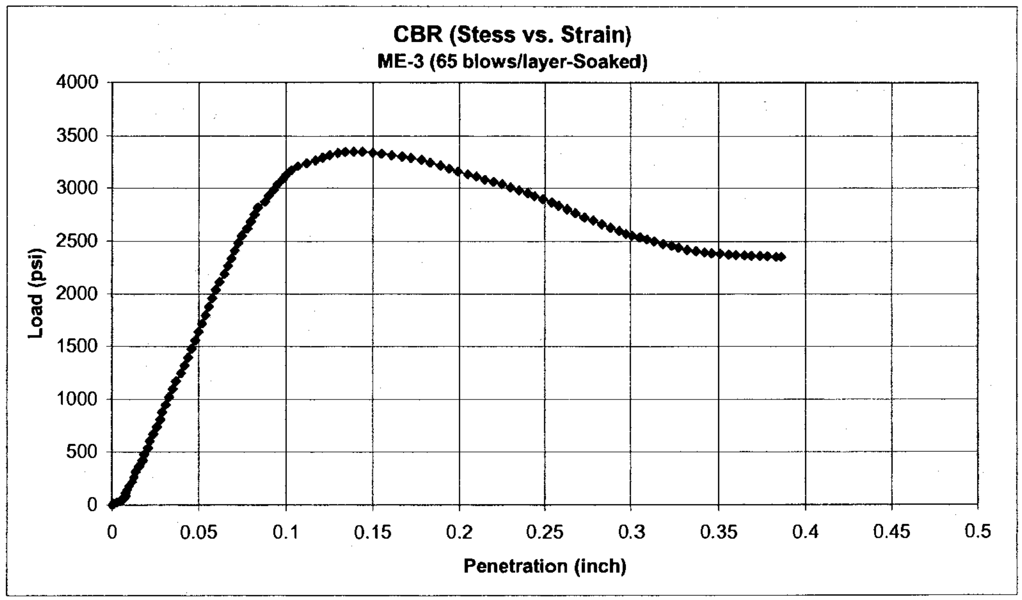
Percent Swell	0.00218157

Sample Mass (g)	[illegible]
Sample Mass (lb)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	164.1049
Density (Dry) (lb/ft3)	155.2869

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-3		
Test:	Triaxial		
Specimen:	ME-3 CBR-S-1		
Number:	1		
Description:	65 Blows/Layer Soaked		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	07/31/07		
Starting Time	14:07:46		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	114		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	77	0.001	17.3102853	5.77201911	
9.99994	282	0.003	63.3961098	21.139083	
14.9999	469	0.005	105.435374	35.1568436	

Load-1 (psi)	3125.061	Load-2 (psi)	3159.993
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	312.506	CBR (0.2)	210.666

Reported CBR	312.5

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	182.30	173.00	31.2	5.8[illegible]
2	189.20	180.50	30.2	5.7[illegible]

Average Moisture Content
5.8374

Height Before (in)	0.4810
Height After (in)	0.4830

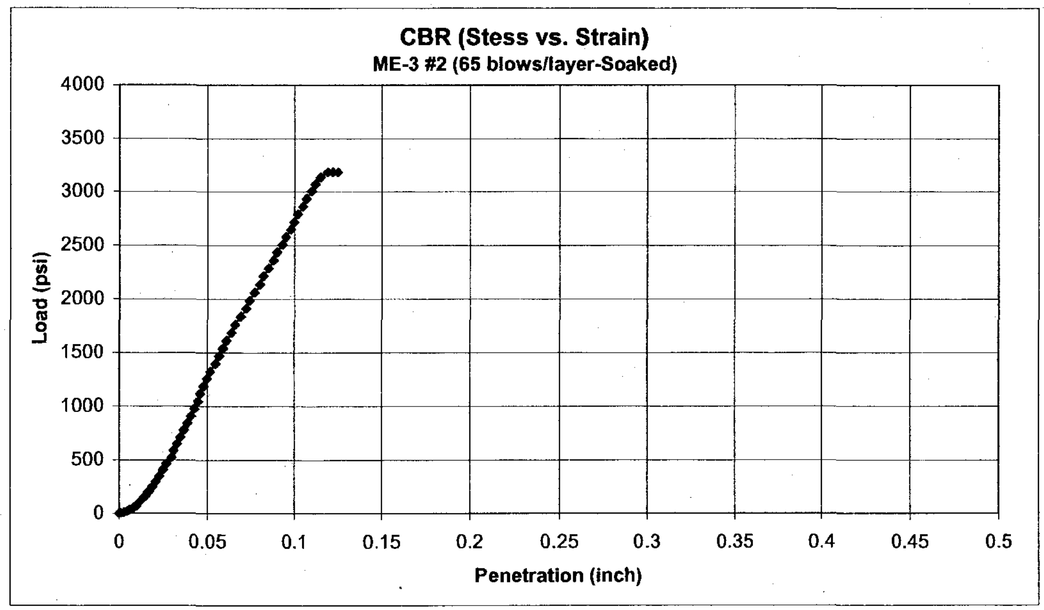
Percent Swell	0.04363137

Sample Mass (g)	5054.00
Sample Mass (lb)	11.14[illegible]
Volume (ft3)	[illegible]

Density (Wet) (lb/ft3)	148.5556
Density (Dry) (lb/ft3)	140.3621

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82	
Project:	DeRocchi Tests			
Customer:	_ERRCO Sample 1			
Sample:	ME-3			
Test:	Triaxial			
Specimen:	ME-3 CBR-S-2			
Number:		2		
Description:	_			
Container ID	_			
Type:	Sand	Soft		
Specific Gra		2.7		
Height of Pla		0 (mm)		
Diametral Me		0 (mm)		
Mass of Initia		0 (gr)		
Mass of Fina		0 (gr)		
Mass of Fina		0 (gr)		
Starting Date	08/17/07			
Starting Time	7:10:27			
Test Results	Stopped by user!			
Stages:		1		
Stage Index:		1		
	Type:	Universal		
	Specimen:			
		Height:	200	(mm)
		Axial Gauge	200	(mm)
		Diameter:	100	(mm)
		Area:	78.54	cm^2
		Volume:	1570.8	cm^3
Data Points:		111		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-5	0	-1.1240445	-0.3748064	2.999
4.99997	35	0.001	7.8683115	2.62364505	
9.99994	131	0.003	29.4499659	9.81992861	

Load-1 (psi)	3002.275	Load-2 (psi)	
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	300.227	CBR (0.2)	0.000

Reported CBR	300.2

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 21 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	180.10	170.20	30.4	[illegible]
2	173.00	163.00	30.7	[illegible]

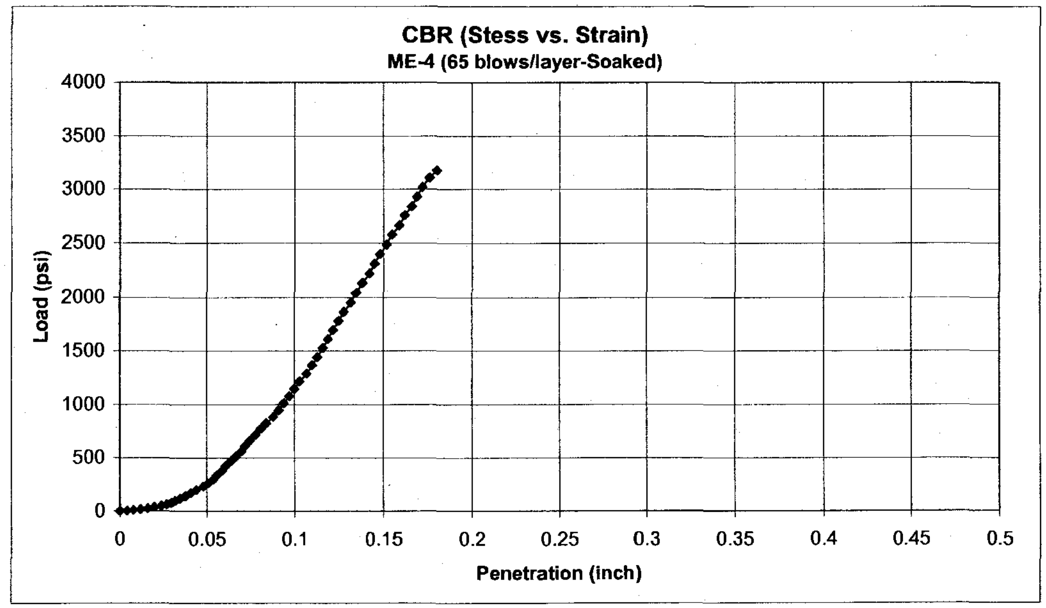
Average Moisture Content
7.3201

Height Before (in)	0.4861
Height After (in)	0.4800
Percent Swell	-0.1330757

Sample Mass (g)	[illegible]
[illegible]	[illegible]
Volume (cu ft)	[illegible]
Density (Wet) (lb/ft3)	148.2206
Density (Dry) (lb/ft3)	138.1108

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-4		
Test:	Triaxial		
Specimen:	CBR-S-1		
Number:		1	
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra\		2.7	
Height of Pla		0 (mm)	
Diametral Me		0 (mm)	
Mass of Initia		0 (gr)	
Mass of Fina		0 (gr)	
Mass of Fina		0 (gr)	
Starting Date	08/21/07		
Starting Time	13:31:23		
Test Results	Stopped by user!		
Stages:		1	
Stage Index:		1	
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:		60	



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	0	0	0	0	
9.99994	33	0.004	7.4186937	2.47372247	

Load-1 (psi)	2578.743	Load-2 (psi)	2578.743
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	257.874	CBR (0.2)	171.916

Reported CBR	257.9

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 29 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	140.50	132.20	31.5	[illegible]
2	155.60	147.30	31.1	[illegible]

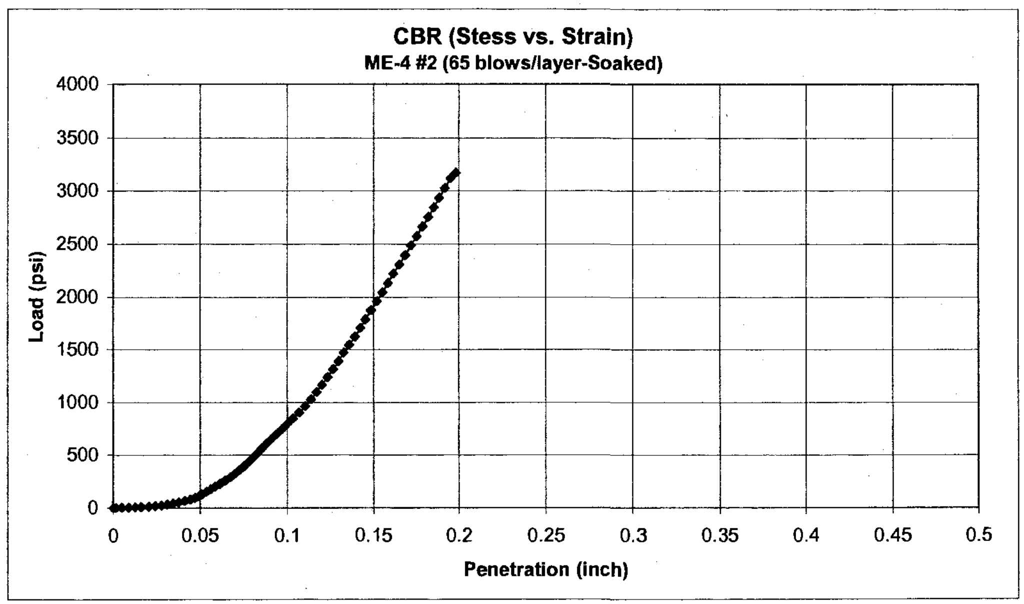
Average Moisture Content
7.6216

Height Before (in)	0.5690
Height After (in)	0.5600
Percent Swell	-0.1963411

Sample Mass (g)	5914.10
[illegible]	[illegible]
Volume [illegible]	[illegible]
Density (Wet) (lb/ft3)	147.3828
Density (Dry) (lb/ft3)	136.9454

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-4		
Test:	Triaxial		
Specimen:	ME-4 CBR-S-1		
Number:	8		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	08/29/07		
Starting Time	7:16:30		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	68		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-8	0.0001	-1.7984712	-0.5996903	2.999
4.99997	4	0.0019	0.8992356	0.29984515	
9.99994	27	0.0052	6.0698403	2.02395475	
14.9999	42	0.009	9.4419738	3.14837406	

Load-1 (psi)	2573.421	Load-2 (psi)	2573.421
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	257.342	CBR (0.2)	171.561

Reported CBR	257.3

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-5)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 7 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	174.40	166.00	30.4	[illegible]
2	[illegible]	[illegible]	30.5	[illegible]

Average Moisture Content
6.2705

Height Before (in)	0.5175
Height After (in)	0.5180

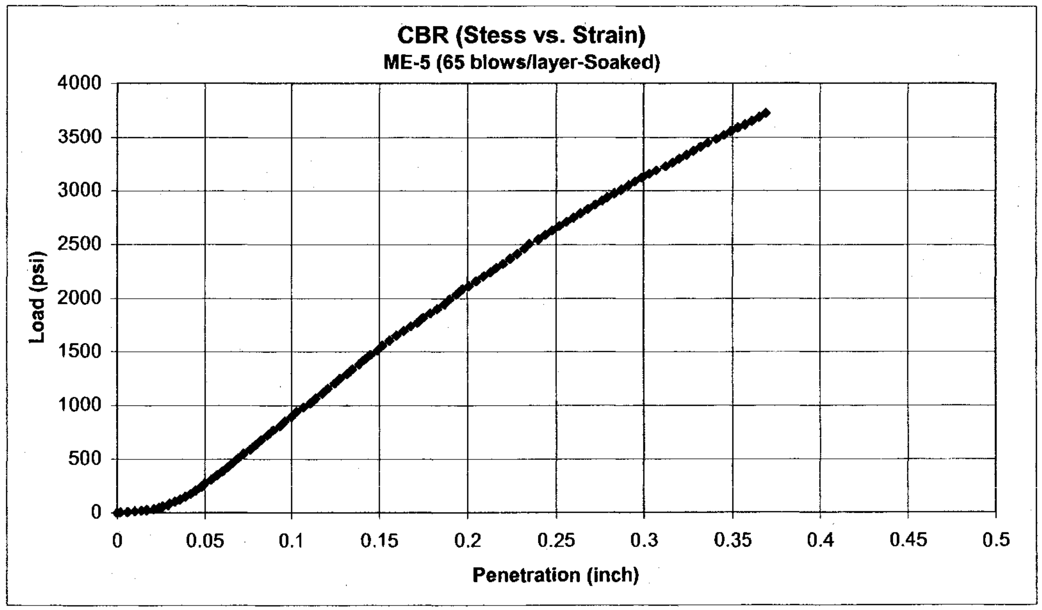
Percent Swell	0.01090784

Sample Mass (g)	5171.60
Sample Mass (lb)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	151.9947
Density (Dry) (lb/ft3)	143.0262

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-5		
Test:	Triaxial		
Specimen:	ME-5 CBR-S-1		
Number:	1		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Grav	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	7/8/2007		
Starting Time	12:05:43		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	104		



1E+131

Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	13	0	2.9225157	0.97449673	2.999
4.99997	37	0.002	8.3179293	2.77356762	
9.99994	91	0.006	20.4576099	6.82147713	

Load-1 (psi)	1243.233	Load-2 (psi)	2412.629
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	124.323	CBR (0.2)	160.842

Reported CBR	124.3

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-5)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 6 September 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample #	W1 (g)	W2 (g)	Wc (g)	w
1	[illegible]	172.40	30.2	[illegible]
2	[illegible]	[illegible]	30.4	[illegible]

Average Moisture Content
6.3599

Height Before (in)	0.5510
Height After (in)	0.5371

Percent Swell	-0.303238

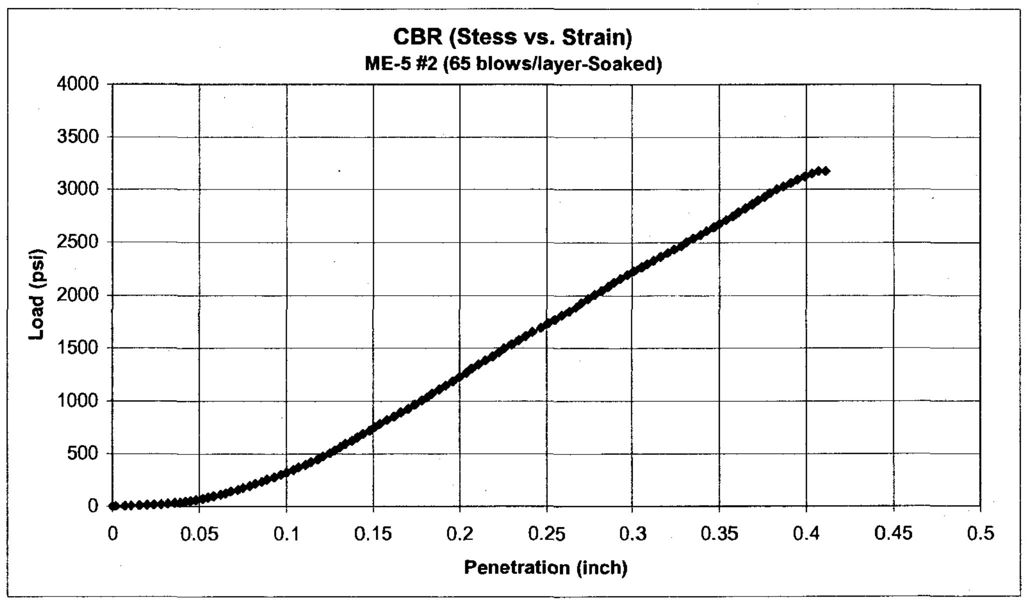
Sample Mass (g)	[illegible]
Sample Height (in)	[illegible]
Volume	[illegible]

Density (Wet) (lb/ft3)	156.5978
Density (Dry) (lb/ft3)	147.2339

AASHTO T-193 (California Bearing Ratio)

Import of GCTS Testing Data:

Software: GCTS C.A.T Version: 1.82
Project: DeRocchi Tests
Customer: _ERRCO Sample 1
Sample: ME-5
Test: Triaxial
Specimen: ME-5 CBR-S-2
Number: 2
Description: _
Container ID _
Type: Sand Soft
Specific Gra 2.7
Height of Pla 0 (mm)
Diametral Me 0 (mm)
Mass of Initia 0 (gr)
Mass of Fina 0 (gr)
Mass of Fina 0 (gr)
Starting Date 6/9/2007
Starting Time 11:49:36
Test Results Stopped by user!
Stages: 1
Stage Index: 1
Type: Universal
Specimen:
Height: 200 (mm)
Axial Gauge 200 (mm)
Diameter: 100 (mm)
Area: 78.54 cm^2
Volume: 1570.8 cm^3
Data Points: 116



1E+131

Time	CBR Axial Lc	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	16	0.002	3.5969424	1.19938059	
9.99994	39	0.007	8.7675471	2.9234902	
14.9999	64	0.011	14.3877696	4.79752237	

Load-1 (psi)	1030.343	Load-2 (psi)	2003.865
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	103.034	CBR (0.2)	133.591

Reported CBR	103.0

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-6)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 7 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	168.80	157.60	30.4	8.8050
2	174.80	163.40	30.7	8.5908

Average Moisture Content
8.6979

Height Before (in)	0.5139
Height After (in)	0.5065

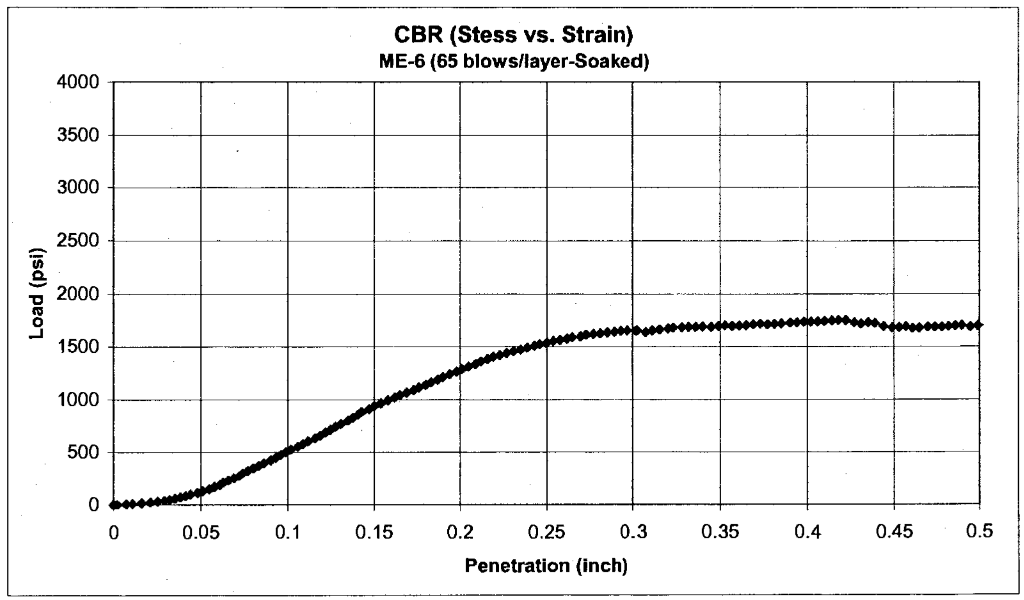
Percent Swell	-0.1614361

Sample Mass (g)	[illegible]
Sample Height (in)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	137.095
Density (Dry) (lb/ft3)	126.1248

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-6		
Test:	Triaxial		
Specimen:	ME-6 CBR-S-1		
Number:	1		
Description:	65 blows/layer Soaked		
Container ID	_		
Type:	Rock	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	7/8/2007		
Starting Time	12:33:01		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1
sec	N	inch
0.00097637	0	0
4.99997	20	0.002
9.99994	67	0.007
14.9999	114	0.011

Axial Load (lb-f)	Axial Load (psi)
0	0
4.496178	1.49922574
15.0621963	5.02240624
25.6282146	8.54558673

Area (sq in)
2.999

Load-1 (psi)	989.939	Load-2 (psi)	1560.394
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	98.994	CBR (0.2)	104.026

Reported CBR	99.0

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-6)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	155.30	148.50	30.4	[illegible]
2	163.70	155.95	30.4	[illegible]

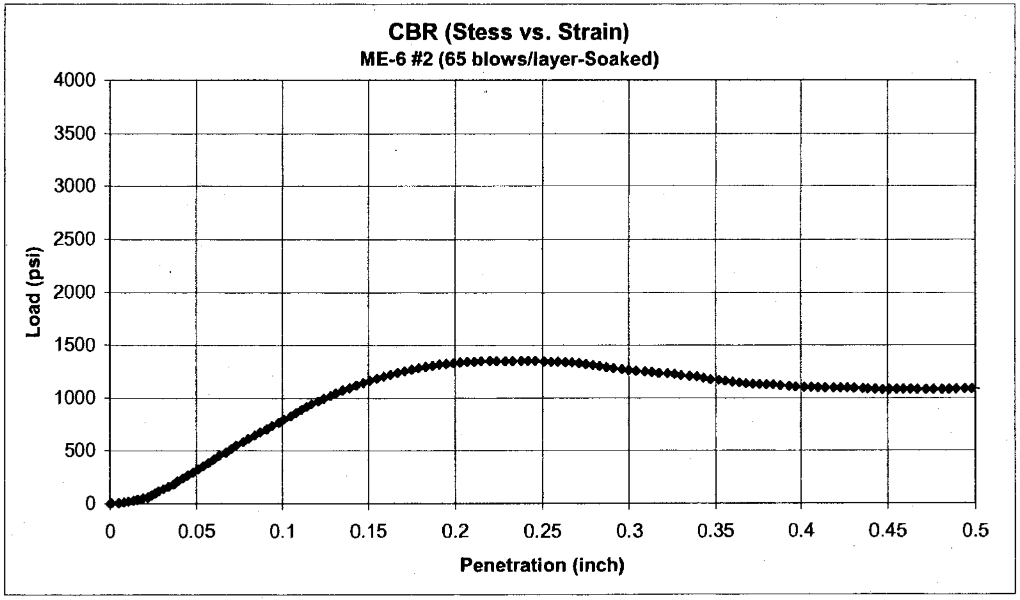
Average Moisture Content
5.9441

Height Before (in)	0.7965
Height After (in)	0.4900
Percent Swell	-6.6865069

Sample Mass (g)	45[illegible].70
[illegible]	[illegible]
[illegible]	[illegible]
Density (Wet) (lb/ft3)	138.1415
Density (Dry) (lb/ft3)	130.3908

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-6		
Test:	Triaxial		
Specimen:	ME-6 CBR-S-2		
Number:	4		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	08/17/07		
Starting Time	8:16:49		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	29	0.001	6.5194581	2.17387733	
9.99994	80	0.005	17.984712	5.99690297	
14.9999	153	0.008	34.3957617	11.4690769	

Load-1 (psi)	939.115	Load-2 (psi)	1344.506
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	93.912	CBR (0.2)	89.634

Reported CBR	93.9

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-7)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)   w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	143.10	138.80	30.5	[illegible]
2	190.10	178.80	30.1	[illegible]

Average Moisture Content
7.5146

Height Before (in)	0.4943
Height After (in)	0.4860

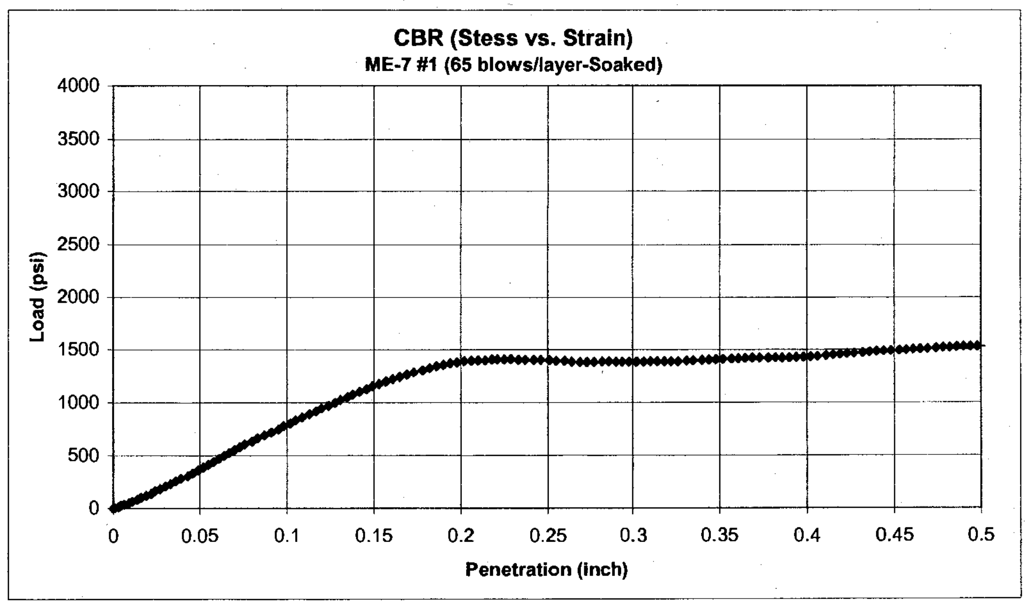
Percent Swell	-0.1799794

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	131.6014
Density (Dry) (lb/ft3)	122.4032

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82	
Project:	DeRocchi Tests			
Customer:	_ERRCO Sample 1			
Sample:	ME-7			
Test:	Triaxial			
Specimen:	ME-7-CBR-S-1			
Number:	1			
Description:	_			
Container ID	_			
Type:	Sand	Soft		
Specific Gra	2.7			
Height of Pla	0	(mm)		
Diametral Me	0	(mm)		
Mass of Initia	0	(gr)		
Mass of Fina	0	(gr)		
Mass of Fina	0	(gr)		
Starting Date	08/17/07			
Starting Time	8:54:38			
Test Results	Completed			
Stages:	1			
Stage Index:	1			
	Type:	Universal		
	Specimen:			
		Height:	200	(mm)
		Axial Gauge	200	(mm)
		Diameter:	100	(mm)
		Area:	78.54	cm^2
		Volume:	1570.8	cm^3
Data Points:	146			



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	46	0.001	10.3412094	3.44821921	
9.99994	166	0.003	37.3182774	12.4435737	
14.9999	313	0.004	70.3651857	23.4628829	

Load-1 (psi)	798.188	Load-2 (psi)	1388.658
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	79.819	CBR (0.2)	92.577

Reported CBR	79.8

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-7)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 29 August 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	124.60	116.50	30.4	[illegible]
2	143.70	135.00	30.7	[illegible]

Average Moisture Content
8.8745

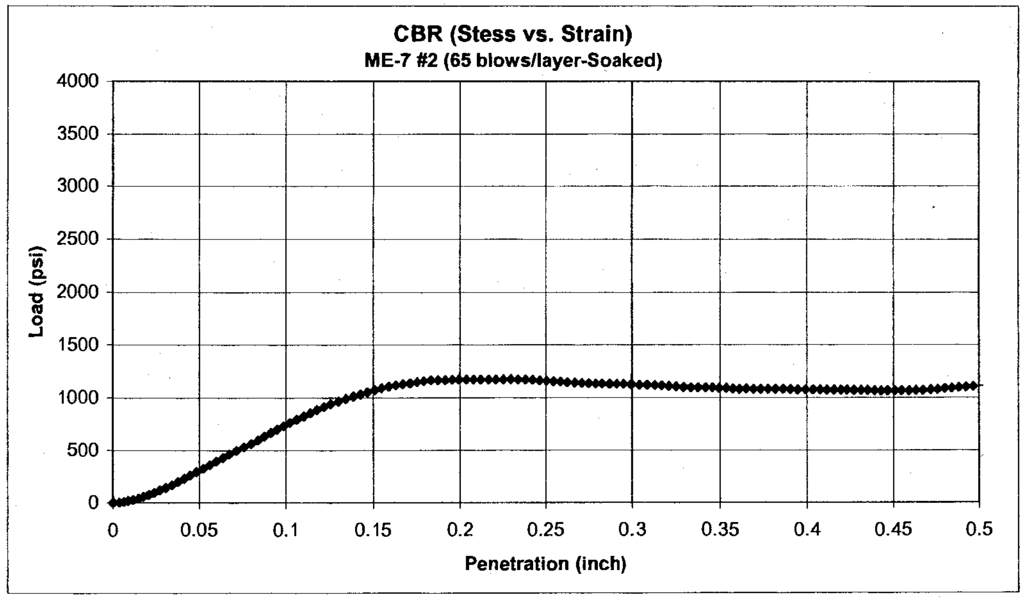
Height Before (in)	0.4638
Height After (in)	0.4635
Percent Swell	-0.0065447

Sample Mass (g)	4527.01
[illegible]	[illegible]
[illegible]	[illegible]
Density (Wet) (lb/ft3)	136.0045
Density (Dry) (lb/ft3)	124.9186

AASHTO T-193 (California Bearing Ratio)

Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-7		
Test:	Triaxial		
Specimen:	ME-7 CBR-S-2		
Number:	3		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0	(mm)	
Diametral Me	0	(mm)	
Mass of Initi	0	(gr)	
Mass of Fina	0	(gr)	
Mass of Fina	0	(gr)	
Starting Date	08/29/07		
Starting Time	7:42:51		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-3	0	-0.6744267	-0.2248839	2.999
4.99997	-1	0.0004	-0.2248089	-0.0749613	
9.99994	55	0.0037	12.3644895	4.12287079	
14.9999	130	0.0065	29.225157	9.74496732	

Load-1 (psi)	762.581	Load-2 (psi)	1170.745
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	76.258	CBR (0.2)	78.050

Reported CBR	76.3

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-8)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 13 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	152.40	145.00	30.4	[illegible]
2	[illegible]	151.30	30.4	[illegible]

Average Moisture Content
6.6478

Height Before (in)	0.5421
Height After (in)	0.5510

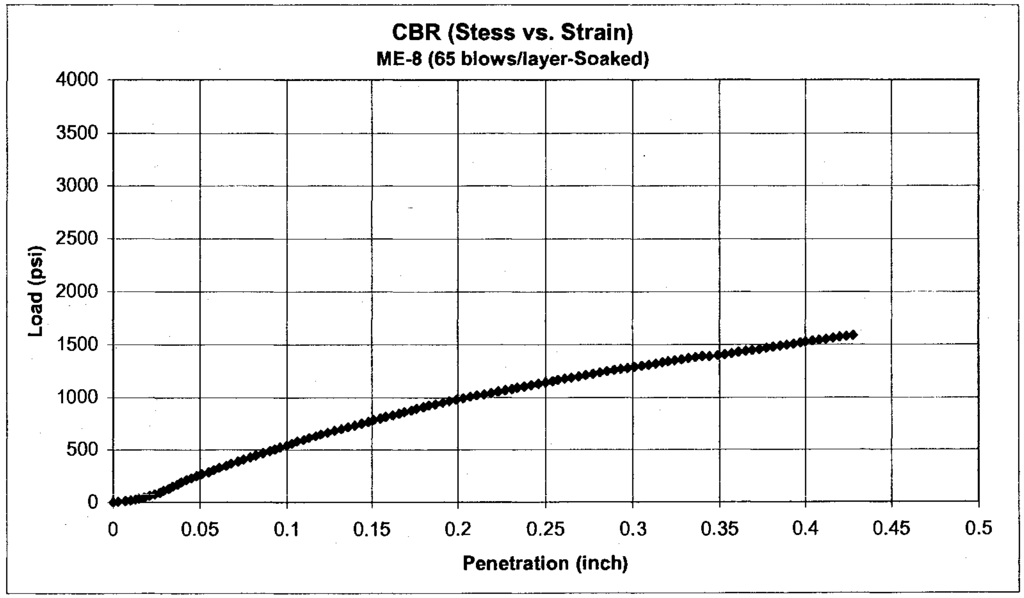
Percent Swell	0.19415958

Sample Mass (g)	[illegible]
Sample Mass (lb)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	140.1667
Density (Dry) (lb/ft3)	131.4295

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82	
Project:	DeRocchi Tests			
Customer:	_ERRCO Sample 1			
Sample:	ME-8			
Test:	Triaxial			
Specimen:	ME-8 CBR-S-1			
Number:	1			
Description:	_			
Container ID	_			
Type:	Sand	Soft		
Specific Gra	2.7			
Height of Pla	0	(mm)		
Diametral Me	0	(mm)		
Mass of Initia	0	(gr)		
Mass of Fina	0	(gr)		
Mass of Fina	0	(gr)		
Starting Date	08/13/07			
Starting Time	10:49:43			
Test Results	Completed			
Stages:	1			
Stage Index:	1			
	Type:	Universal		
	Specimen:			
		Height:	200	(mm)
		Axial Gauge	200	(mm)
		Diameter:	100	(mm)
		Area:	78.54	cm^2
		Volume:	1570.8	cm^3
Data Points:	146			



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq In)
0.00097637	0	0	0	0	2.999
4.99997	0	0	0	0	
9.99994	0	0	0	0	
14.9999	75	0.003	16.8606675	5.62209653	

Load-1 (psi)	542.045	Load-2 (psi)	975.321
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	54.205	CBR (0.2)	65.021

Reported CBR	54.2

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-8)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 21 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	w
1	[illegible]	[illegible]	30.4	[illegible]
2	160.10	150.10	30.4	[illegible]

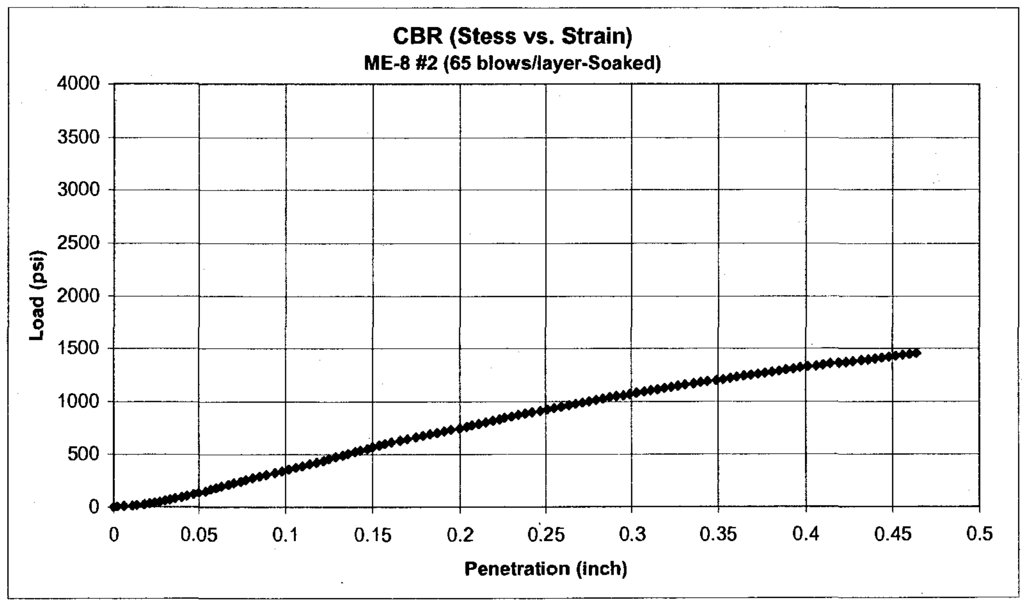
Average Moisture Content
8.3868

Height Before (in)	0.5010
Height After (in)	0.4880
Percent Swell	-0.2836039

Sample Wet (g)	[illegible]
Sample Mass (lb)	[illegible]
Vol. Tested (ft)	[illegible]
Density (Wet) (lb/ft3)	139.6876
Density (Dry) (lb/ft3)	128.8788

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-8		
Test:	Triaxial		
Specimen:	ME-8 CBR-S-2		
Number:	5		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	08/21/07		
Starting Time	12:42:50		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	47	0.002	10.5660183	3.52318049	
9.99994	106	0.006	23.8297434	7.94589643	
14.9999	178	0.011	40.0159842	13.3431091	

Load-1 (psi)	488.523	Load-2 (psi)	857.482
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	48.852	CBR (0.2)	57.165

Reported CBR	48.9

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-9)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 30 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w (%)
1	164.20	153.20	30.6	[illegible]
2	178.70	167.50	30.5	[illegible]

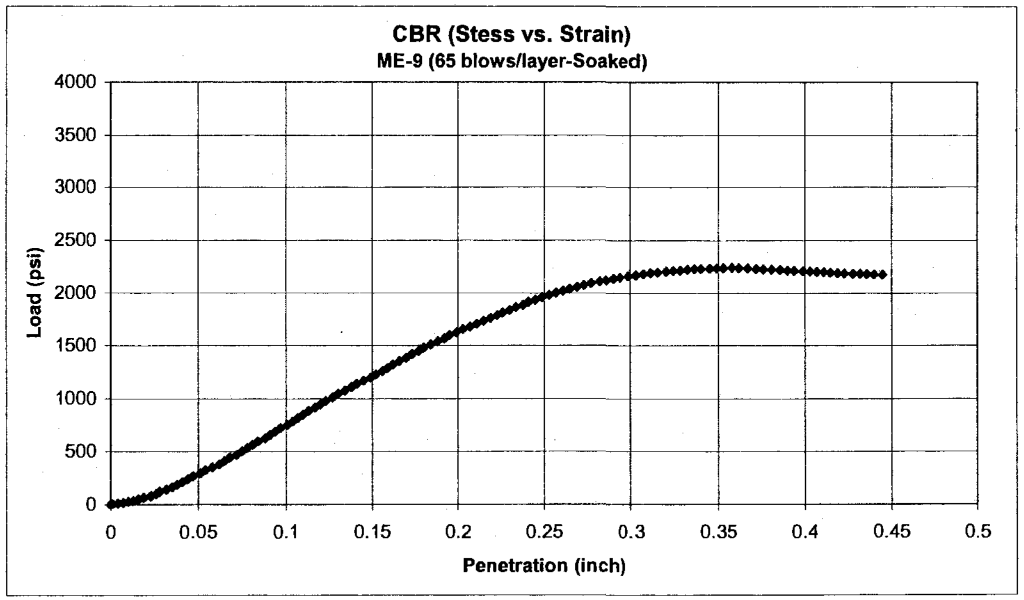
Average Moisture Content
8.9387

Height Before (in)	0.4959
Height After (in)	0.5530
Percent Swell	1.24567551

Sample Mass (g)	[illegible]
[illegible]	[illegible]
Volume [illegible]	[illegible]
Density (Wet) (lb/ft3)	134.9611
Density (Dry) (lb/ft3)	123.8872

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software: GCTS C.A.T Version: 1.82
Project: DeRocchi Tests
Customer: _ERRCO Sample 1
Sample: ME-9
Test: Triaxial
Specimen: ME-9 CBR-S-1
Number: 1
Description: CBR 65 (65 blows/layer - Soaked)
Container ID _
Type: Sand Soft
Specific Gra 2.7
Height of Pla 0 (mm)
Diametral Me 0 (mm)
Mass of Initia 0 (gr)
Mass of Fina 0 (gr)
Mass of Fina 0 (gr)
Starting Date 07/30/07
Starting Time 16:11:18
Test Results Stopped by user!
Stages: 1
Stage Index: 1
Type: Universal
Specimen:
Height: 200 (mm)
Axial Gauge 200 (mm)
Diameter: 100 (mm)
Area: 78.54 cm^2
Volume: 1570.8 cm^3
Data Points: 136



Time sec	CBR Axial Lc N	LVDT #1 inch	Axial Load (lb-f)	Axial Load (psi)	Area (sq in)
0.00097637	0	0	0	0	2.999
4.99997	44	0.001	9.8915916	3.29829663	
9.99994	114	0.004	25.6282146	8.54558673	
14.9999	211	0.007	47.4346779	15.8168316	

Load-1 (psi)	912.804	Load-2 (psi)	1731.081
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	91.280	CBR (0.2)	115.405

Reported CBR	91.3

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ME-9)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 20 Aug 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100

W1 = mass of container and moist soil (g)

W2 = mass of container and oven dried soil (g)

Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w
1	132.60	120.80	30.3	[illegible]
2	155.30	144.80	30.7	[illegible]

Average Moisture Content
10.4100

Height Before (in)	0.5295
Height After (in)	0.5119

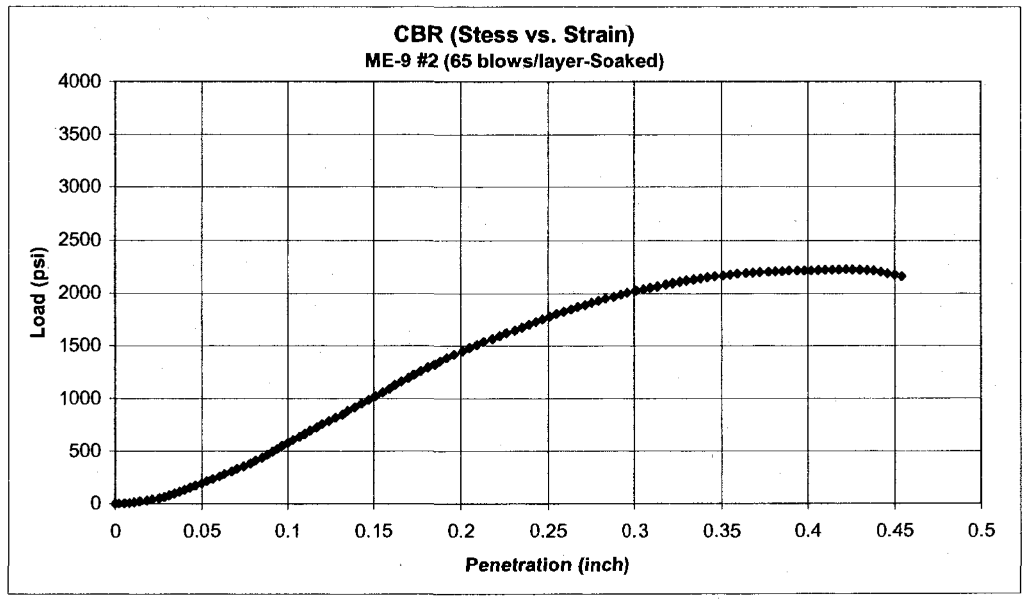
Percent Swell	-0.383956

Sample Mass (g)	4842.00
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	136.4454
Density (Dry) (lb/ft3)	123.5807

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ME-9		
Test:	Triaxial		
Specimen:	ME-9 CBR-S-2		
Number:	4		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	08/20/07		
Starting Time	6:10:23		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-8	0	-1.7984712	-0.5996903	2.999
4.99997	17	0.002	3.8217513	1.27434188	
9.99994	35	0.005	7.8683115	2.62364505	
14.9999	90	0.008	20.232801	6.74651584	

Load-1 (psi)	911.005	Load-2 (psi)	1697.723
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	91.100	CBR (0.2)	113.182

Reported CBR	91.1

Mark DeRocchi / Dan Balbo
UNH
C&D Materials Testing (ERRCO #2)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 17 Apr 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1	96.50	87.50	30.8	15.8730
2	93.90	85.30	30.6	15.7221

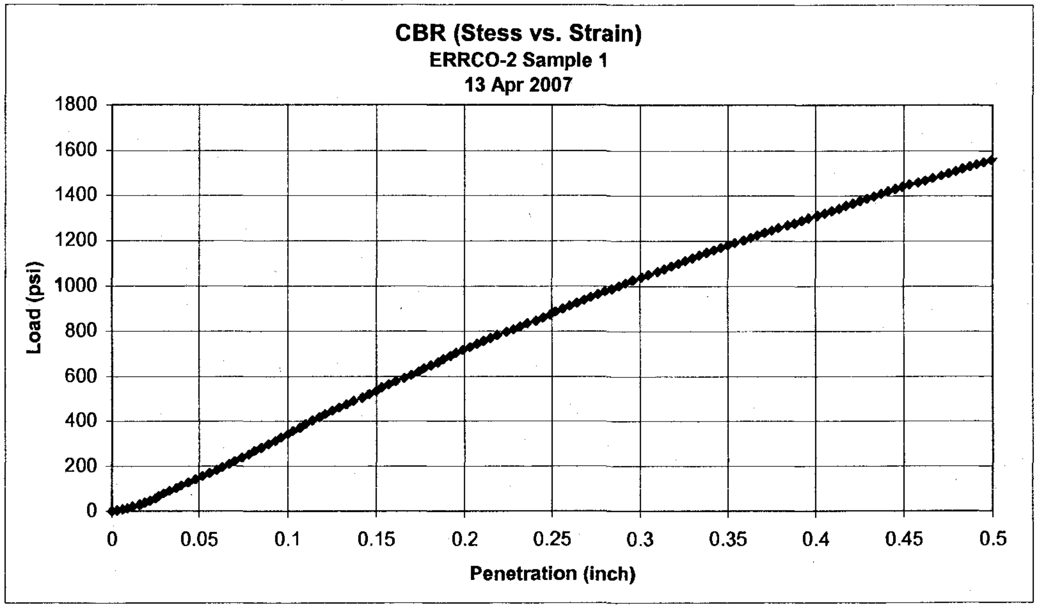
Average Moisture Content
15.7976

Sample Mass (g)	4578.00
Sample Mass (lb)	10.0927
V mold (cu ft)	0.075[illegible]

Density (Wet) (lb/ft3)	134.5643
Density (Dry) (lb/ft3)	116.2065

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ERRCO 2		
Test:	Triaxial		
Specimen:	ERRCO 2-1		
Number:	5		
Description:	CBR 20 Blows/Layer		
Container ID	ERRCO Sample 3		
Type:	Rock	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	4/13/2007		
Starting Time	10:45:22		
Test Results	Stopped by user!		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	133		



Time	CBR Axial Lo	LVDT_1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	0	0	0	0	
9.99994	37	0.003	8.3179293	2.77356762	

Load-1 (psi)	386.500	Load-2 (psi)	755.985
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	38.650	CBR (0.2)	50.399

Reported CBR	38.650

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO #2)

Location: Gregg Hall, Durham, NH (UNH)
Date: 17 July 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w (%)
1	91.30	83.60	30.4	14.4737
2	111.30	101.10	30.4	14.4272

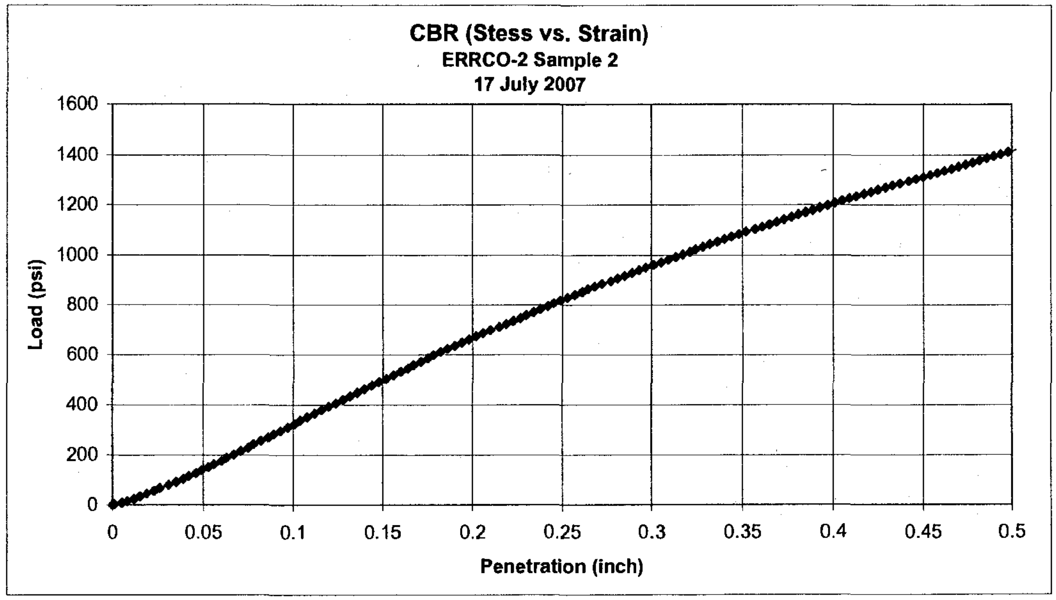
Average Moisture Content (%)
14.4504

Sample Mass (g)	[illegible]
Sample Mass (lb)	[illegible]
Volume (cu ft)	[illegible]

Density (Wet) (lb/f	120.4259
Density (Dry) (lb/f	105.221

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software: GCTS C.A.T Version: 1.82
Project: DeRocchi Tests
Customer: _ERRCO Sample 1
Sample: ERRCO 2
Test: Triaxial
Specimen: ERRCO 2-2
Number: 1
Description: _
Container ID _
Type: Sand Soft
Specific Gra 2.7
Height of Pla 0 (mm)
Diametral Me 0 (mm)
Mass of Initia 0 (gr)
Mass of Fina 0 (gr)
Mass of Fina 0 (gr)
Starting Date 7/17/2007
Starting Time 7:57:01
Test Results Stopped by user!
Stages: 1
Stage Index: 1
Type: Universal
Specimen:
Height: 200 (mm)
Axial Gauge 200 (mm)
Diameter: 100 (mm)
Area: 78.54 cm^2
Volume: 1570.8 cm^3
Data Points: 162



Time sec	Axial Load N	LVDT #1 inch	Axial Load (lb-f)	Axial Load (psi)	Area (sq in)
0.00097637	0	0	0	0	2.999
4.99997	27	0.001	6.0698403	2.023954752	
9.99994	98	0.005	22.0312722	7.346206135	
14.9999	194	0.008	43.6129266	14.5424897	

Load-1 (psi)	364.012	Load-2 (psi)	698.040
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	36.401	CBR (0.2)	40.891

Reported CBR	40.9

Mark DeRocchi / Dan Balbo
UNH
C&D Materials Testing (ERRCO #3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 17 Apr 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1	96.50	87.50	30.8	15.8730
2	93.90	85.30	30.6	15.7221

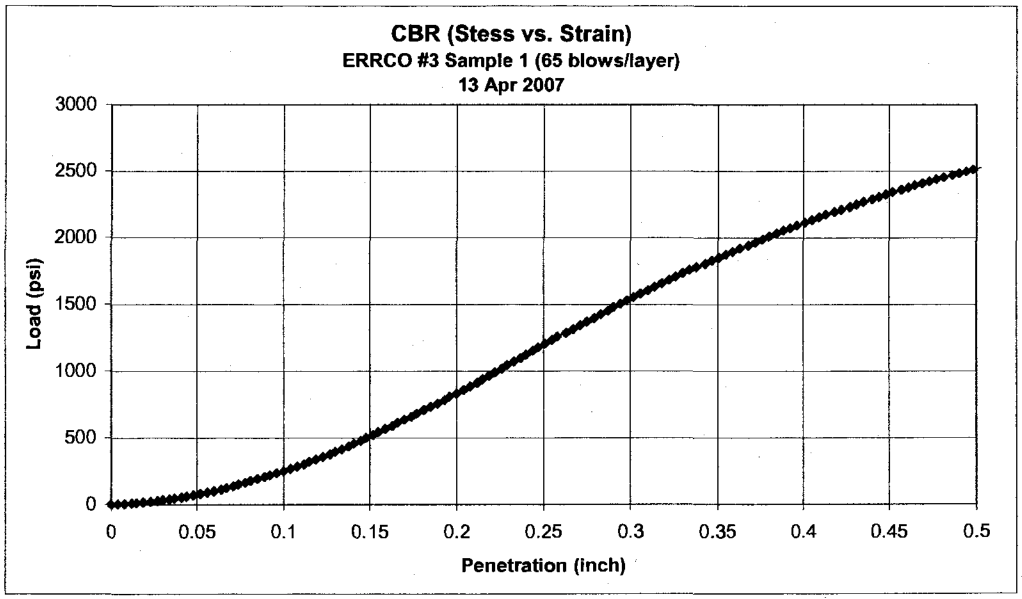
Average Moisture Content
15.7976

Sample Mass (g)	[illegible]
Sample Mass (lb)	10.0927
Volume (cu ft)	[illegible]

Density (Wet) (lb/ft3)	134.5643
Density (Dry) (lb/ft3)	116.2065

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82	
Project:	DeRocchi Tests			
Customer:	_ERRCO Sample 1			
Sample:	ERRCO 3			
Test:	Triaxial			
Specimen:	ERRCO 3 CBR (65)			
Number:	7			
Description:	CBR 65 Blows/Layer			
Container ID	Sample #2 Bucket			
Type:	Rock	Soft		
Specific Gra	2.7			
Height of Pla	0	(mm)		
Diametral Me	0	(mm)		
Mass of Initia	0	(gr)		
Mass of Fina	0	(gr)		
Mass of Fina	0	(gr)		
Starting Date	4/13/2007			
Starting Time	12:29:28			
Test Results	Stopped by user!			
Stages:	1			
Stage Index:	1			
	Type:	Universal		
	Specimen:			
		Height:	200	(mm)
		Axial Gauge	200	(mm)
		Diameter:	100	(mm)
		Area:	78.54	cm^2
		Volume:	1570.8	cm^3
Data Points:	144			



Time	CBR Axial Lo	LVDT_1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-4	0	-0.8992356	-0.2998451	2.999
4.99997	0	0	0	0	
9.99994	35	0.004	7.8683115	2.62364505	
14.9999	72	0.008	16.1862408	5.39721267	

Load-1 (psi)	706.360	Load-2 (psi)	1395.030
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	70.636	CBR (0.2)	93.002

Reported CBR	70.636

Mark DeRocchi / Dan Balbo
UNH
C&D Materials Testing (ERRCO #3)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 17 Apr 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)

w = moisture content (%)
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

w = ((W1-W2)/(W2-Wc))*100

Sample	W1(g)	W2(g)	Wc(g)	w
1	96.50	87.50	30.8	15.8730
2	93.90	85.30	30.6	15.7221

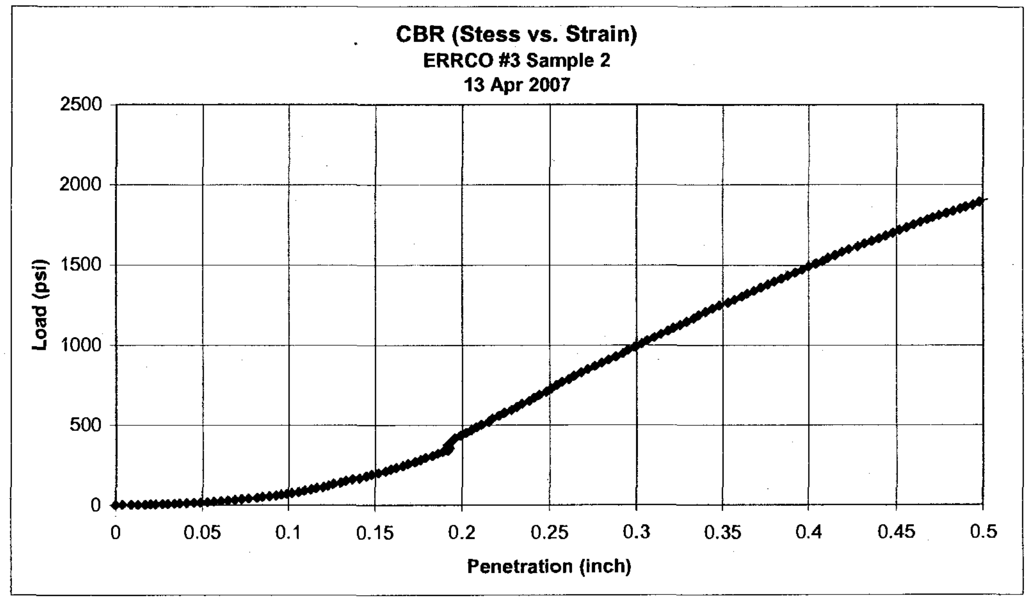
Average Moisture Content
15.7976

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	134.5643
Density (Dry) (lb/ft3)	**116.2065**

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ERRCO 3		
Test:	Triaxial		
Specimen:	ERRCO3 CBR S-2		
Number:	10		
Description:	CBR 30 sec vibe hammer / layer		
Container ID	Sample #2 Bucket		
Type:	Rock	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	4/13/2007		
Starting Time	15:01:53		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT_1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	-8	0	-1.7984712	-0.5996903	2.999
4.99997	0	0	0	0	
9.99994	15	0.004	3.3721335	1.12441931	
14.9999	24	0.009	5.3954136	1.79907089	

Load-1 (psi)	501.791	Load-2 (psi)	1047.059
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	50.179	CBR (0.2)	69.804

Reported CBR	**69.804**

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 6 Setember 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1 (g)	W2 (g)	Wc (g)	w (%)
1	147.90	130.00	30.4	[illegible]
2	151.30	141.50	30.7	[illegible]

Average Moisture Content
17.6670

Height Before (in)	0.5371
Height After (in)	0.5010

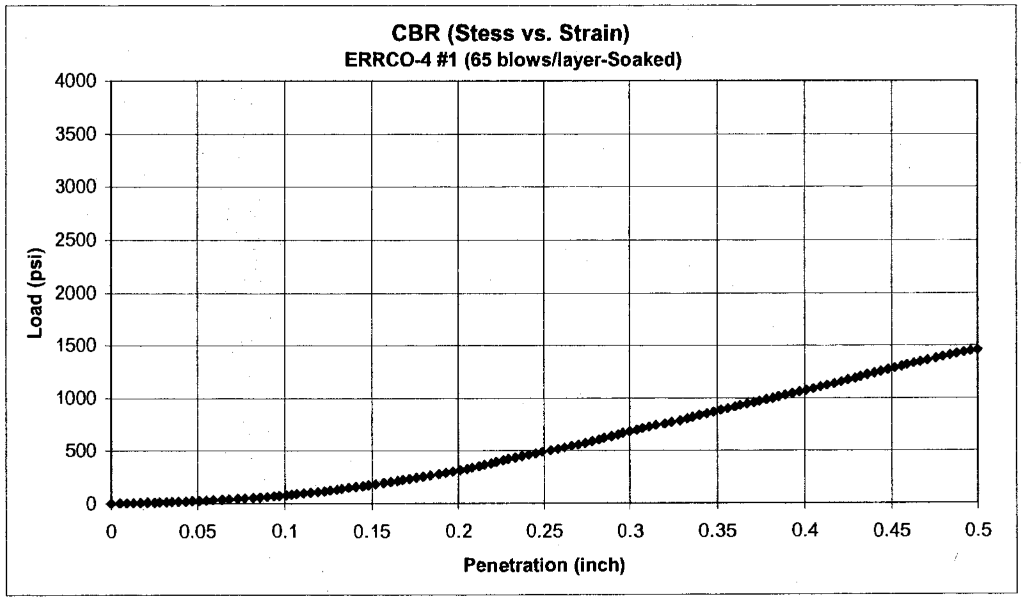
Percent Swell	-0.7875462

Sample Mass (g)	4594.80
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	135.0581
Density (Dry) (lb/ft3)	114.7799

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ERRCO 4		
Test:	Triaxial		
Specimen:	ERRCO 4 CBR-S-1		
Number:	9		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	6/9/2007		
Starting Time	12:33:17		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time sec	CBR Axial Lo N	LVDT #1 inch	Axial Load (lb-f)	Axial Load (psi)	Area (sq in)
0.00097637	0	0	0	0	2.999
4.99997	0	0	0	0	
9.99994	24	0.005	5.3954136	1.79907089	
14.9999	43	0.009	9.6667827	3.22333535	

Load-1 (psi)	500.591	Load-2 (psi)	867.002
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	50.059	CBR (0.2)	57.800

Reported CBR	50.1

Mark DeRocchi / John Westover
UNH
C&D Materials Testing (ERRCO-4)

Location: Kingsbury Hall, Durham, NH (UNH)
Date: 18 Setember 2007

AASHTO T-265 (Lab Determination of Moisture Content of Soils)
w = moisture content (%) w = ((W1-W2)/(W2-Wc))*100
W1 = mass of container and moist soil (g)
W2 = mass of container and oven dried soil (g)
Wc = mass of container

Sample	W1(g)	W2(g)	Wc(g)	W
1	166.10	148.30	30.8	15.1489
2	160.60	143.30	30.6	15.3505

Average Moisture Content
15.2497

Height Before (in)	0.5910
Height After (in)	0.5880

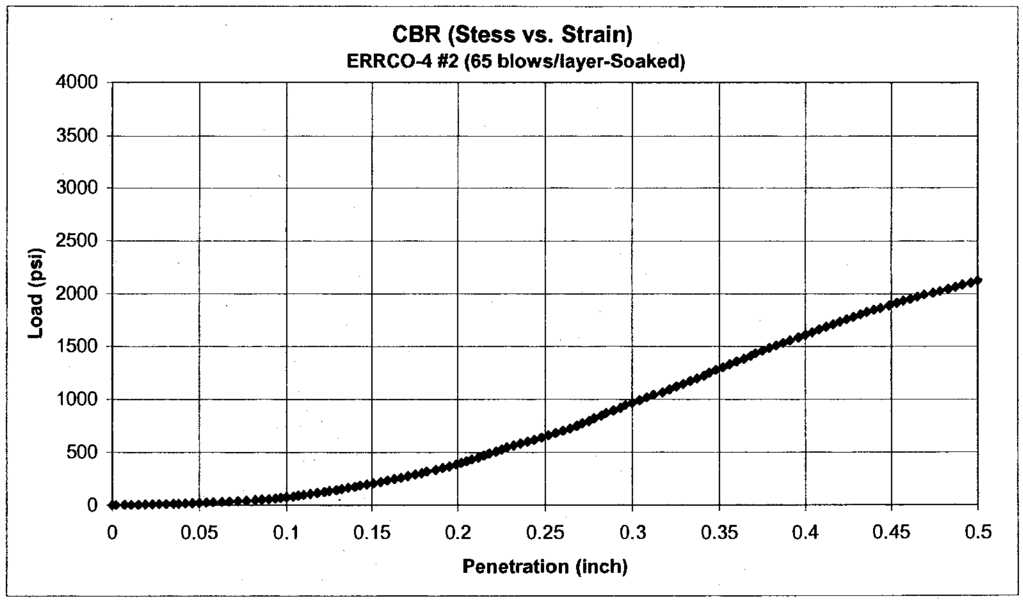
Percent Swell	-0.065447

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

Density (Wet) (lb/ft3)	135.9928
Density (Dry) (lb/ft3)	117.9984

AASHTO T-193 (California Bearing Ratio)
Import of GCTS Testing Data:

Software:	GCTS C.A.T Version:		1.82
Project:	DeRocchi Tests		
Customer:	_ERRCO Sample 1		
Sample:	ERRCO 4		
Test:	Triaxial		
Specimen:	ERRCO 4 CBR-S-2		
Number:	11		
Description:	_		
Container ID	_		
Type:	Sand	Soft	
Specific Gra	2.7		
Height of Pla	0 (mm)		
Diametral Me	0 (mm)		
Mass of Initia	0 (gr)		
Mass of Fina	0 (gr)		
Mass of Fina	0 (gr)		
Starting Date	09/18/07		
Starting Time	11:25:12		
Test Results	Completed		
Stages:	1		
Stage Index:	1		
	Type:	Universal	
	Specimen:		
		Height:	200 (mm)
		Axial Gauge	200 (mm)
		Diameter:	100 (mm)
		Area:	78.54 cm^2
		Volume:	1570.8 cm^3
Data Points:	146		



Time	CBR Axial Lo	LVDT #1	Axial Load	Axial Load	Area
sec	N	inch	(lb-f)	(psi)	(sq in)
0.00097637	0	0	0	0	2.999
4.99997	15	0.002	3.3721335	1.12441931	
9.99994	37	0.007	8.3179293	2.77356762	
14.9999	42	0.011	9.4419738	3.14837406	

Load-1 (psi)	637.696	Load-2 (psi)	1274.567
Normalize-1 (psi)	1000.000	Normalize-2 (psi)	1500.000
CBR (0.1)	63.770	CBR (0.2)	84.971

Reported CBR	63.8

APPENDIX E: Resilient Modulus Data

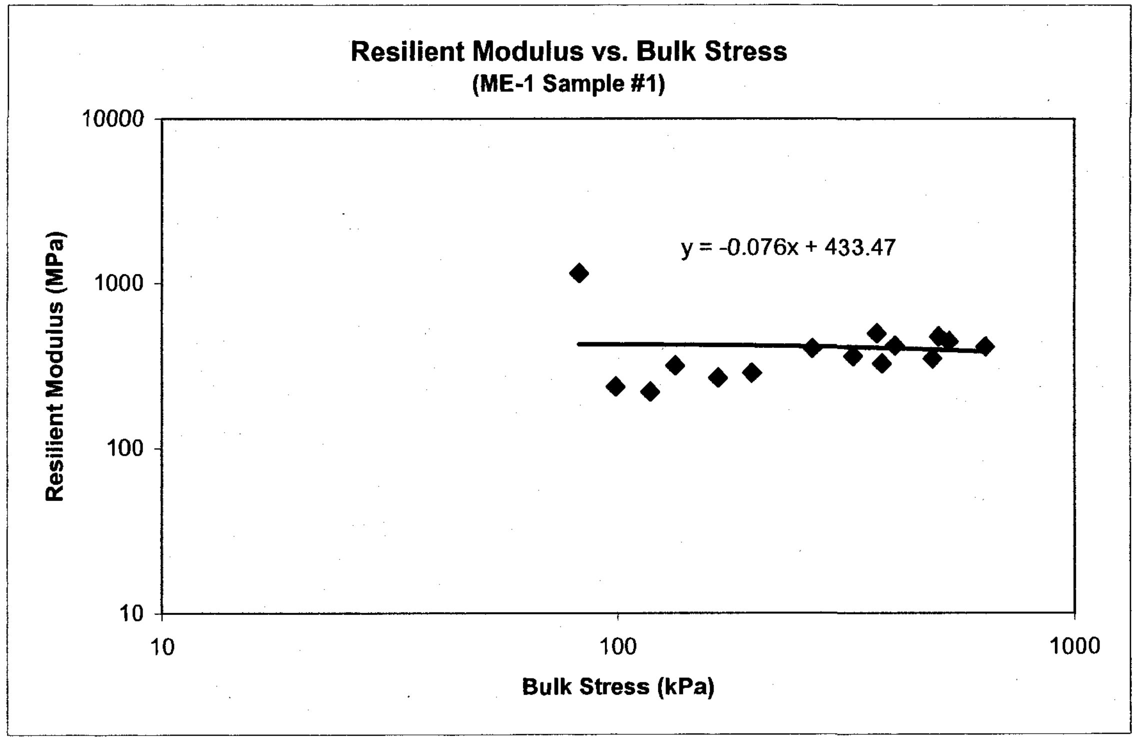
Reduced Data from Testing
ME-1 #1 (9 August 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	82.193	1144.635
2	99.212	235.5468
3	118.327	219.8006
4	133.846	315.5116
5	165.704	267.2487
6	196.497	285.4753
7	266.526	401.0173
8	327.491	359.5124
9	378.744	325.7809
10	368.84	493.6886
11	404.048	416.5184
12	489.237	349.0191
13	505.071	476.0328
14	532.02	443.4196
15	638.597	410.9912

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	144.80	136.00	30.90	8.37%
1b	152.70	143.40	30.40	8.23%

Average Moisture Content
8.3015



Specimen Weight (g)	3681.40
Specimen Height (cm)	18.60
Specimen Wet Density (lb/ft3)	152.4059
Specimen Dry Density (lb/ft3)	140.72

Average	409.6133
Median	359.5124
Gmean	375.5661

Mr Intercept Value	433.47
Mr Slope Value	-0.07600
Mr @ 500 Θ (kPa)	395.47

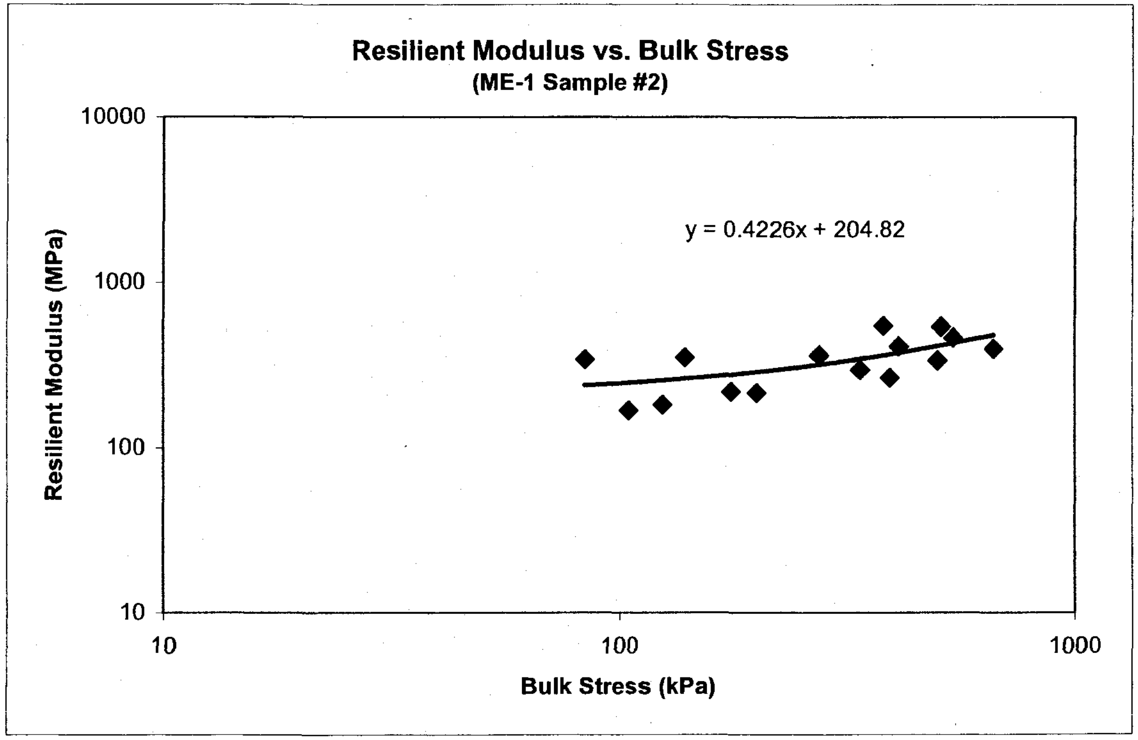
Reduced Data from Testing
ME-1 #2 (20 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	84.24	343.9831
2	104.86	167.3089
3	123.948	181.3092
4	139.425	351.2791
5	176.125	218.1952
6	199.928	214.5002
7	274.33	365.4122
8	337.22	298.2516
9	391.245	268.3499
10	378.701	547.9973
11	409.927	414.385
12	498.947	338.4628
13	508.24	539.8157
14	540.355	467.502
15	663.238	396.8221

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	211.90	199.70	31.20	7.24%
1b	202.80	190.80	30.70	7.50%

Average Moisture Content
7.3678



Specimen Weight (g)	3841.80
Specimen Height (cm)	19.30
Specimen Wet Density (lb/ft3)	153.2778
Specimen Dry Density (lb/ft3)	142.76

Average	340.905
Median	343.9831
Gmean	320.4688

Mr Intercept Value	204.82
Mr Slope Value	0.42260
Mr @ 500 Θ (kPa)	416.12

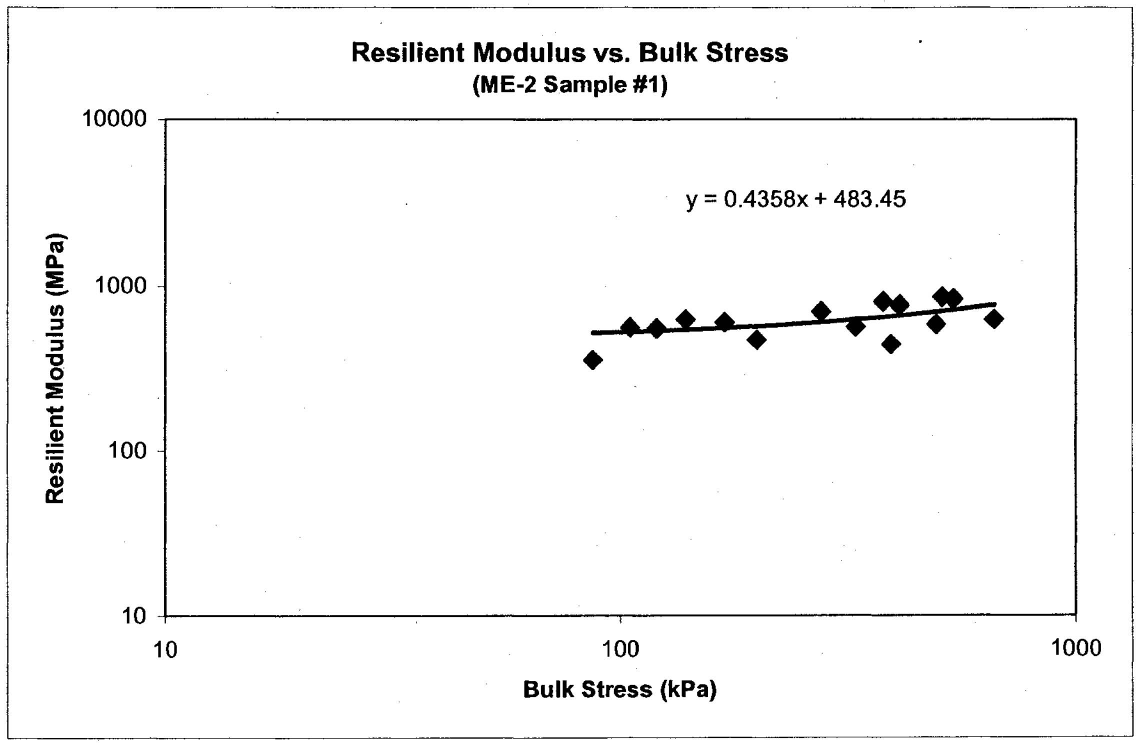
Reduced Data from Testing
ME-2 Sample 1 (14 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	87.369	450.337
2	105.418	709.7217
3	120.25	700.585
4	139.352	794.4372
5	169.603	762.346
6	199.735	597.0365
7	275.825	889.4726
8	329.193	717.189
9	394.702	560.878
10	378.194	1018.392
11	411.125	969.1898
12	496.123	741.6413
13	510.743	1084.055
14	540.749	1059.798
15	664.592	792.4305

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	153.00	144.30	30.40	7.64%
1b	155.20	146.60	30.70	7.42%

Average Moisture Content
7.5292



Specimen Weight (g)	3901.70
Specimen Height (cm)	20.10
Specimen Wet Density (lb/ft3)	149.4719
Specimen Dry Density (lb/ft3)	139.01

Average	623.4275
Median	601.8722
Gmean	606.8265

Mr Intercept Value	483.45
Mr Slope Value	0.43580
Mr @ 500 Θ (kPa)	701.35

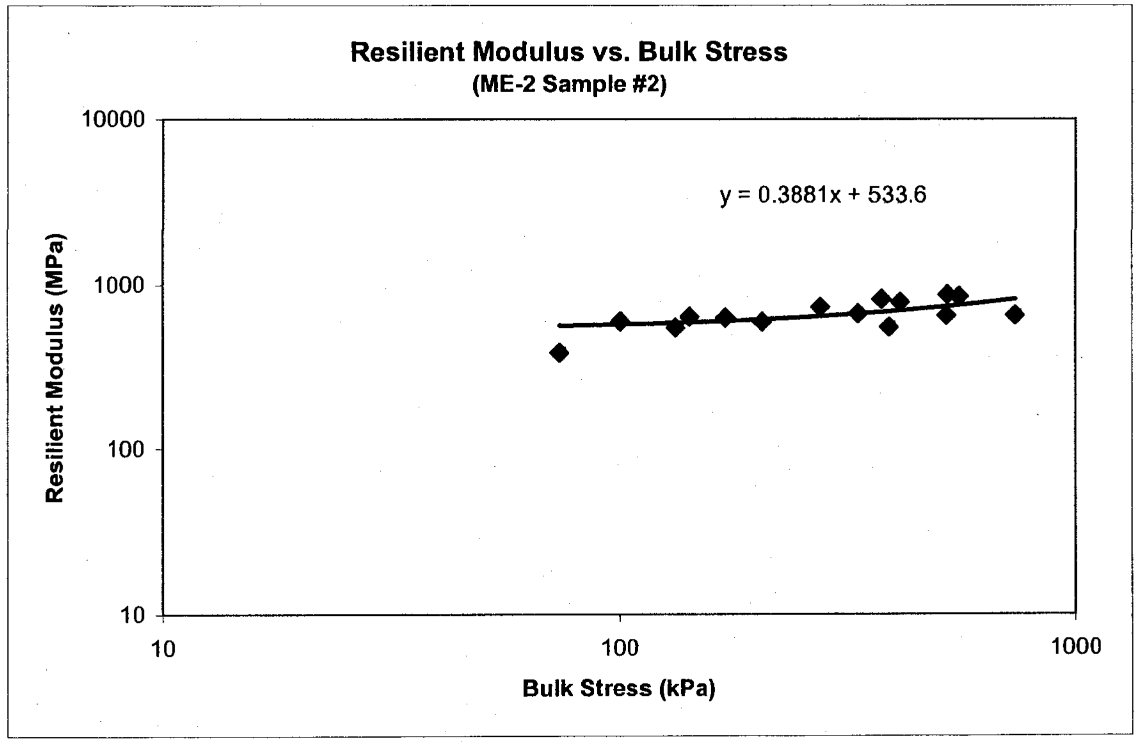
Reduced Data from Testing
ME-2 Sample 2 (14 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	74.29	484.7958
2	100.633	753.4287
3	132.884	692.5491
4	142.694	803.2055
5	171.658	793.7644
6	206.279	748.4775
7	277.534	924.7204
8	335.594	840.5756
9	391.548	694.59
10	377.077	1032.012
11	413.284	993.4305
12	524.109	818.2444
13	526.853	1104.637
14	558.507	1077.068
15	741.075	821.537

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	153.00	144.30	30.40	7.64%
1b	155.20	146.60	30.70	7.42%

Average Moisture Content
7.5292



Specimen Weight (g)	3901.70
Specimen Height (cm)	20.10
Specimen Wet Density (lb/ft3)	149.4719
Specimen Dry Density (lb/ft3)	139.01

Average	662.2871
Median	646.0039
Gmean	649.4456

Mr Intercept Value	533.60
Mr Slope Value	0.38810
Mr @ 500 Θ (kPa)	727.65

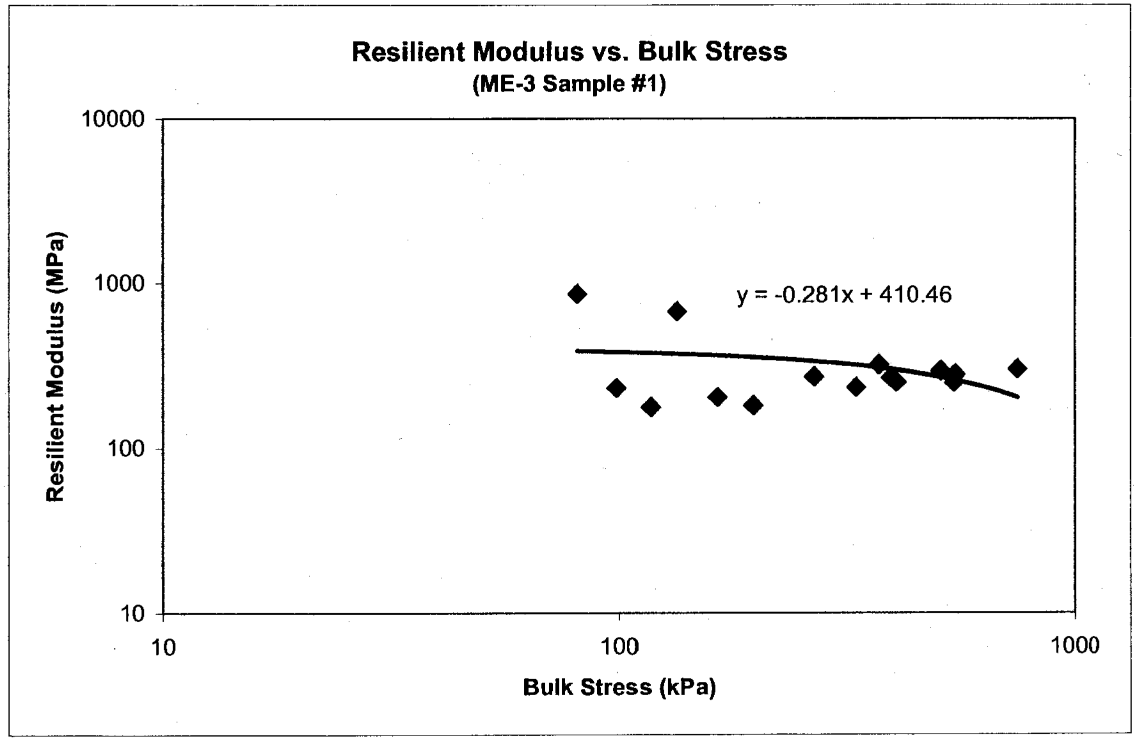
Reduced Data from Testing
ME-3 Sample #1 (28 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	81.072	859.1112
2	98.971	230.7201
3	117.175	175.7928
4	134.277	669.3116
5	164.18	201.7942
6	196.998	180.4432
7	267.464	270.8419
8	330.864	234.5196
9	393.795	267.3707
10	370.989	319.0572
11	405.207	250.194
12	540.294	249.0794
13	505.506	293.2352
14	543.991	278.7602
15	744.466	301.1308

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	W
1a	123.70	117.50	31.00	7.17%
1b	132.40	126.00	30.60	6.71%

Average Moisture Content
6.9381



Specimen Weight (g)	3925.90
Specimen Height (cm)	19.60
Specimen Wet Density (lb/ft3)	154.2357
Specimen Dry Density (lb/ft3)	144.23

Average	318.7575
Median	267.3707
Gmean	286.1413

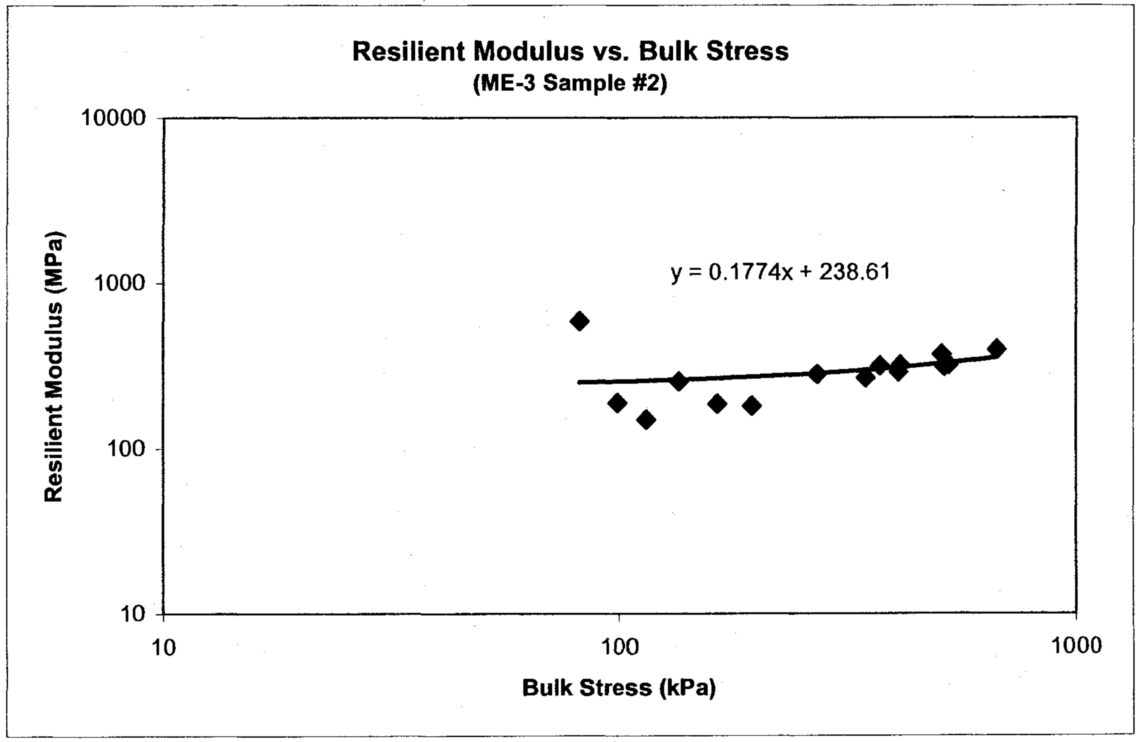
Mr Intercept Value	410.46
Mr Slope Value	-0.28100
Mr @ 500 Θ (kPa)	269.96

Reduced Data from Testing
ME-3 Sample #2 (4 Sep 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	82.258	588.9231
2	99.375	187.0105
3	114.663	149.9777
4	135.117	255.071
5	163.851	185.4385
6	194.655	180.5564
7	270.584	282.9314
8	345.559	268.8663
9	407.887	291.1755
10	371.336	317.5552
11	412.499	320.4913
12	516.537	314.3429
13	509.748	373.5592
14	528.806	321.7353
15	675.447	398.1698

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	158.30	151.50	30.60	5.62%
1b	168.80	161.60	30.50	5.49%



Average Moisture Content
5.5582

Specimen Weight (g)	3712.60
Specimen Height (cm)	19.80
Specimen Wet Density (lb/ft3)	141.3525
Specimen Dry Density (lb/ft3)	136.78

Average	295.7203
Median	291.1755
Gmean	278.8159

Mr Intercept Value	238.61
Mr Slope Value	0.17740
Mr @ 500 Θ (kPa)	327.31

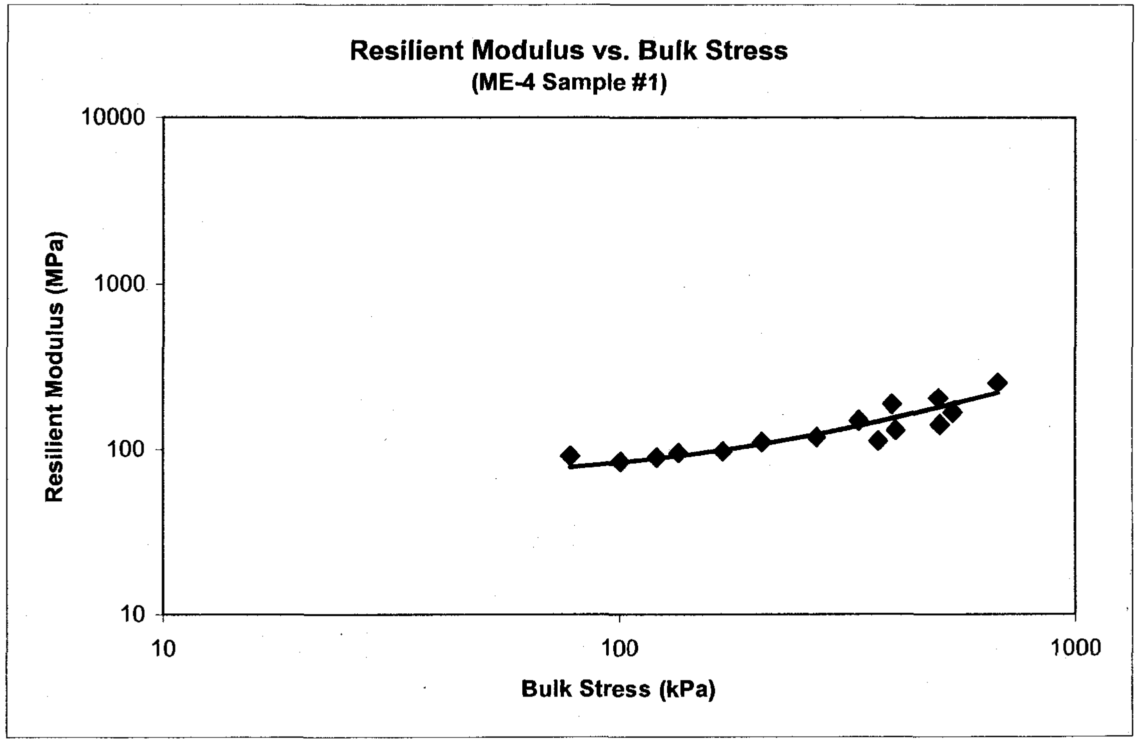
Reduced Data from Testing
ME-4 Sample #1 (27 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Sequence	θ	Mr
1	78.501	91.53957
2	100.857	84.46754
3	120.859	89.46869
4	134.813	95.49994
5	168.759	97.60153
6	205.699	111.1381
7	271.59	118.7207
8	338.29	148.9077
9	400.387	186.4908
10	373.223	113.2146
11	408.042	130.9942
12	506.063	202.9632
13	509.719	141.0586
14	543.698	167.1163
15	679.987	253.1735

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	176.90	166.40	30.30	7.71%
1b	166.80	157.10	31.00	7.69%

Average Moisture Content
7.7036



Specimen Weight (g)	4230.40
Specimen Height (cm)	19.90
Specimen Wet Density (lb/ft3)	[illegible]
Specimen Dry Density (lb/ft3)	151.98

Average	135.4903
Median	118.7207
Gmean	128.3867

Mr Intercept Value	60.14
Mr Slope Value	0.23350
Mr @ 500 Θ (kPa)	176.889

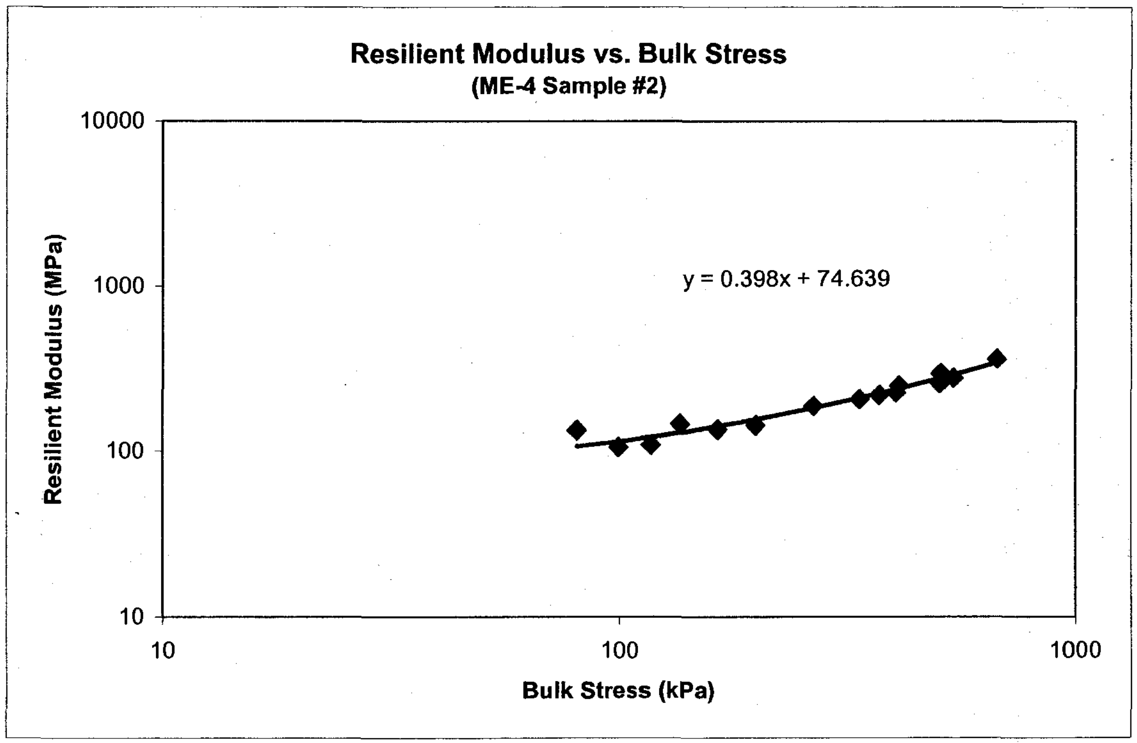
Reduced Data from Testing
ME-4 Sample #2 (27 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	80.971	133.5981
2	99.8	105.822
3	117.704	109.1232
4	136.58	145.0403
5	165.58	134.5198
6	200.834	142.7685
7	268.877	186.4334
8	338.229	204.9694
9	411.29	248.666
10	372.852	216.7383
11	406.413	224.7299
12	507.058	294.2287
13	505.514	255.7799
14	540.862	275.924
15	674.083	362.1477

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	131.60	125.90	30.40	5.97%
1b	143.30	136.90	30.70	6.03%

Average Moisture Content
5.9975



Specimen Weight (g)	3779.20
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	147.7187
Specimen Dry Density (lb/ft3)	139.36

Average	202.6993
Median	204.9694
Gmean	169.812

Mr Intercept Value	74.64
Mr Slope Value	0.39800
Mr @ 500 Θ (kPa)	273.639

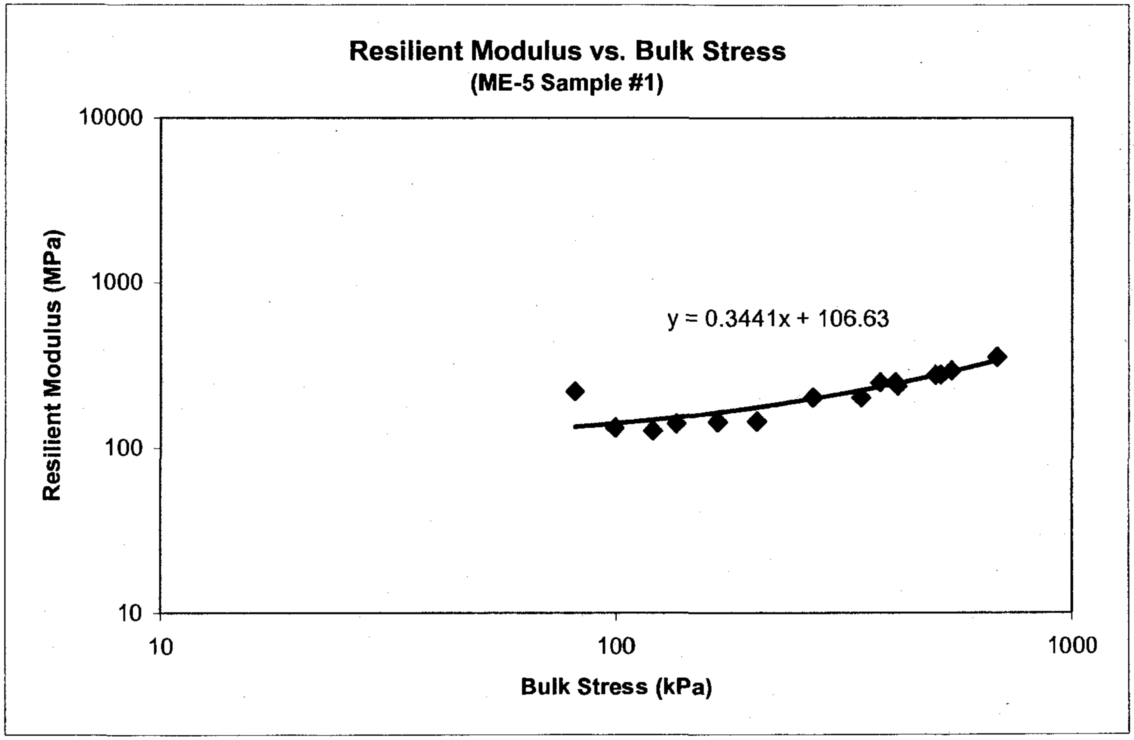
Reduced Data from Testing
ME-5 Sample 1 (20 Sep 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	*θ*	Mr
1	81.168	220.1534
2	99.645	132.7338
3	120.392	127.7269
4	135.606	140.4353
5	166.975	143.8121
6	202.631	145.4237
7	268.586	201.9422
8	341.536	202.5254
9	405.385	251.2105
10	375.553	250.4131
11	410.909	238.8933
12	511.657	278.9512
13	498.502	278.3225
14	540.839	295.9772
15	680.898	356.6139

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	189.70	181.10	30.20	5.70%
1b	168.10	160.50	30.70	5.86%

Average Moisture Content
5.7772



Specimen Weight (g)	3551.70
Specimen Height (cm)	19.80
Specimen Wet Density (lb/ft3)	150.[illegible]
Specimen Dry Density (lb/ft3)	142.71

Average	217.6756
Median	220.1534
Gmean	207.0788

Mr Intercept Value	106.63
Mr Slope Value	0.34410
Mr @ 500 Θ (kPa)	278.68

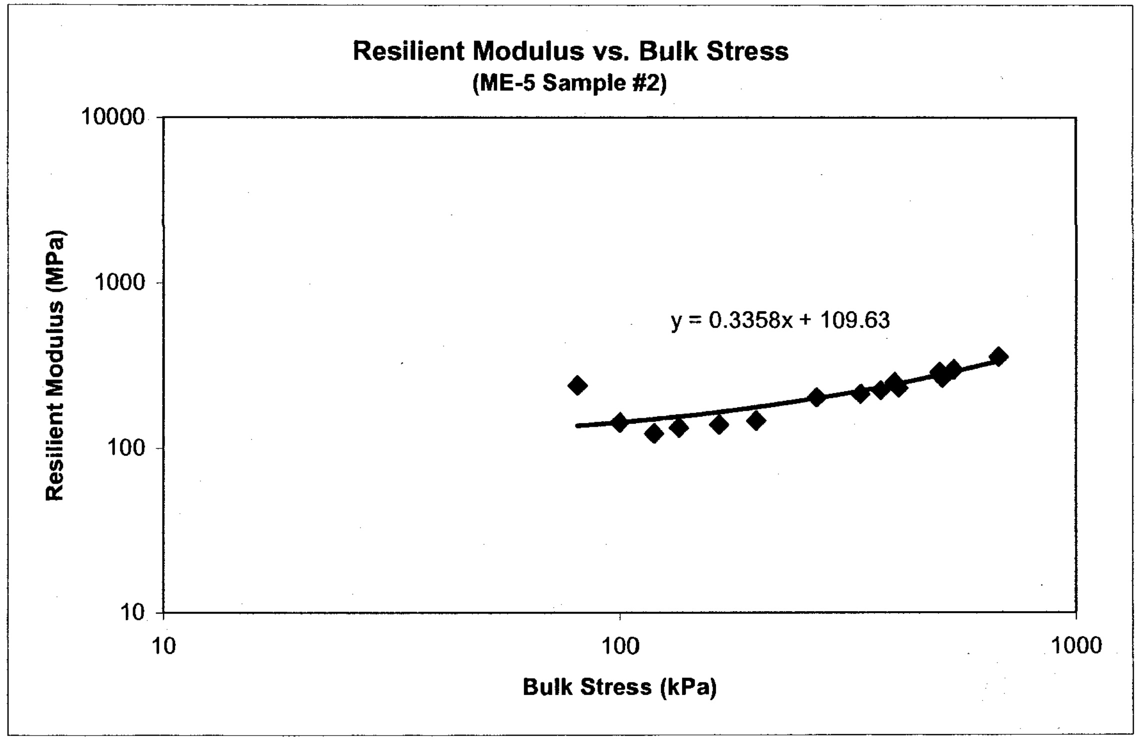
Reduced Data from Testing
ME-5 Sample 2 (20 Sep 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	81.206	240.4208
2	100.101	142.3618
3	118.895	123.0152
4	134.481	133.2428
5	164.558	138.8786
6	198.343	146.7971
7	269.246	202.3429
8	336.259	212.3092
9	400.312	251.043
10	372.922	223.7403
11	408.824	231.824
12	504.251	289.5504
13	511.158	267.9944
14	541.185	300.3654
15	678.192	359.1887

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	W
1a	189.70	181.10	30.20	5.70%
1b	168.10	160.50	30.70	5.86%

Average Moisture Content
5.7772



Specimen Weight (g)	3935.90
Specimen Height (cm)	20.30
Specimen Wet Density (lb/ft3)	[illegible]
Specimen Dry Density (lb/ft3)	141.14

Average	217.5383
Median	223.7403
Gmean	206.6602

Mr Intercept Value	109.63
Mr Slope Value	0.33580
Mr @ 500 Θ (kPa)	277.53

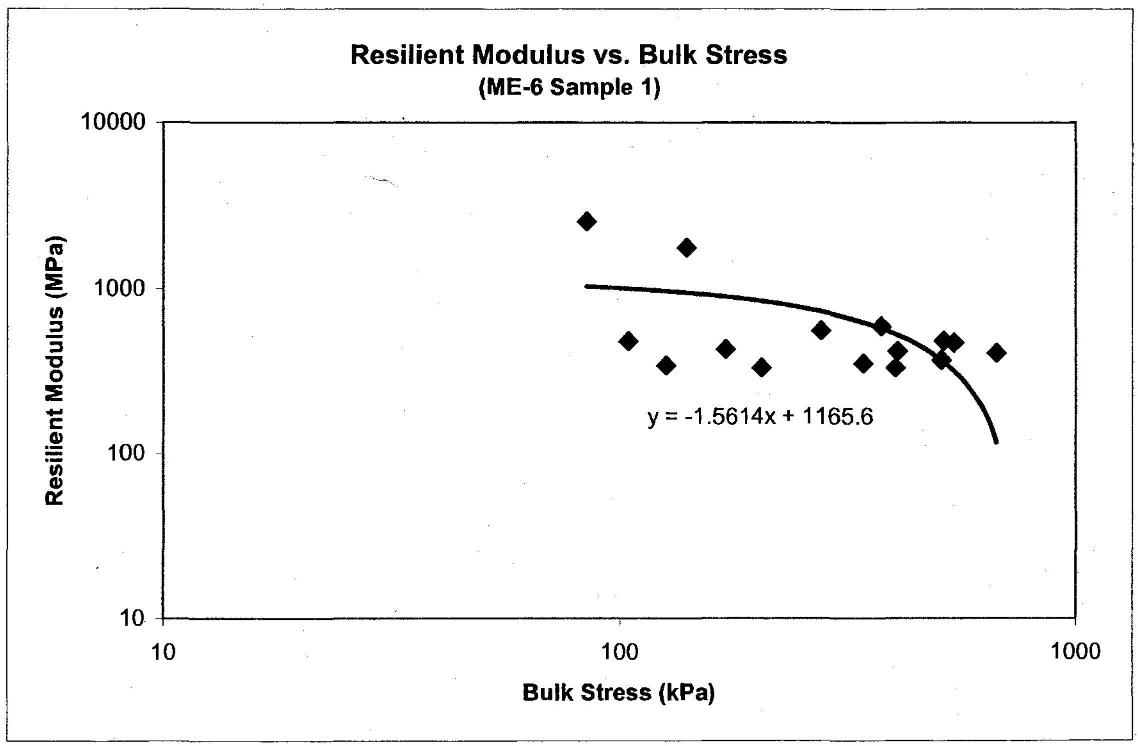
Reduced Data from Testing
ME-6 Sample #1 (20 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	84.693	2532.618
2	104.566	477.0531
3	126.189	341.4848
4	140.277	1759.104
5	171.146	427.9173
6	205.649	329.0462
7	278.599	554.5733
8	344.213	352.1011
9	405.592	332.6126
10	377.355	593.0173
11	409.794	419.9764
12	510.682	370.0291
13	516.354	483.3986
14	543.405	469.9254
15	671.077	406.4974

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	171.60	158.90	30.40	9.88%
1b	162.60	152.10	30.40	8.63%

Average Moisture Content
9.2555



Specimen Weight (g)	3850.00
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	150.4561
Specimen Dry Density (lb/ft3)	137.74

Average	656.6236
Median	427.9173
Gmean	520.9465

Mr Intercept Value	1165.60
Mr Slope Value	-1.56140
Mr @ 500 Θ (kPa)	384.9

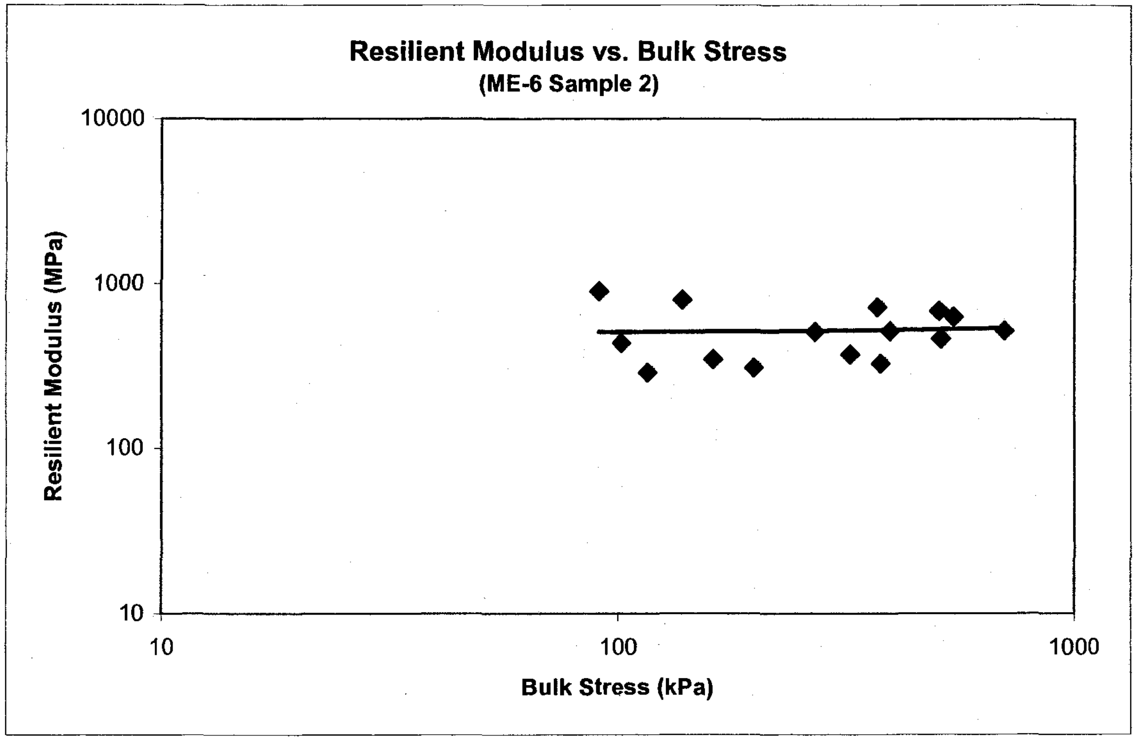
Reduced Data from Testing
ME-6 Sample #2 (22 Aug 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	90.859	890.8799
2	101.942	433.8032
3	116.435	284.0469
4	139.236	791.7967
5	162.188	346.3176
6	199.535	306.9886
7	270.569	507.296
8	322.948	367.7932
9	377.033	323.2751
10	370.951	712.4756
11	395.555	513.6323
12	511.408	462.8673
13	506.145	681.4256
14	544.787	627.454
15	704.915	516.2237

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	153.70	145.10	31.10	7.54%
1b	161.10	152.10	30.70	7.41%

Average Moisture Content
7.4787



Specimen Weight (g)	3728.70
Specimen Height (cm)	19.40
Specimen Wet Density (lb/ft3)	147.9986
Specimen Dry Density (lb/ft3)	137.70

Average	517.7517
Median	507.296
Gmean	487.4437

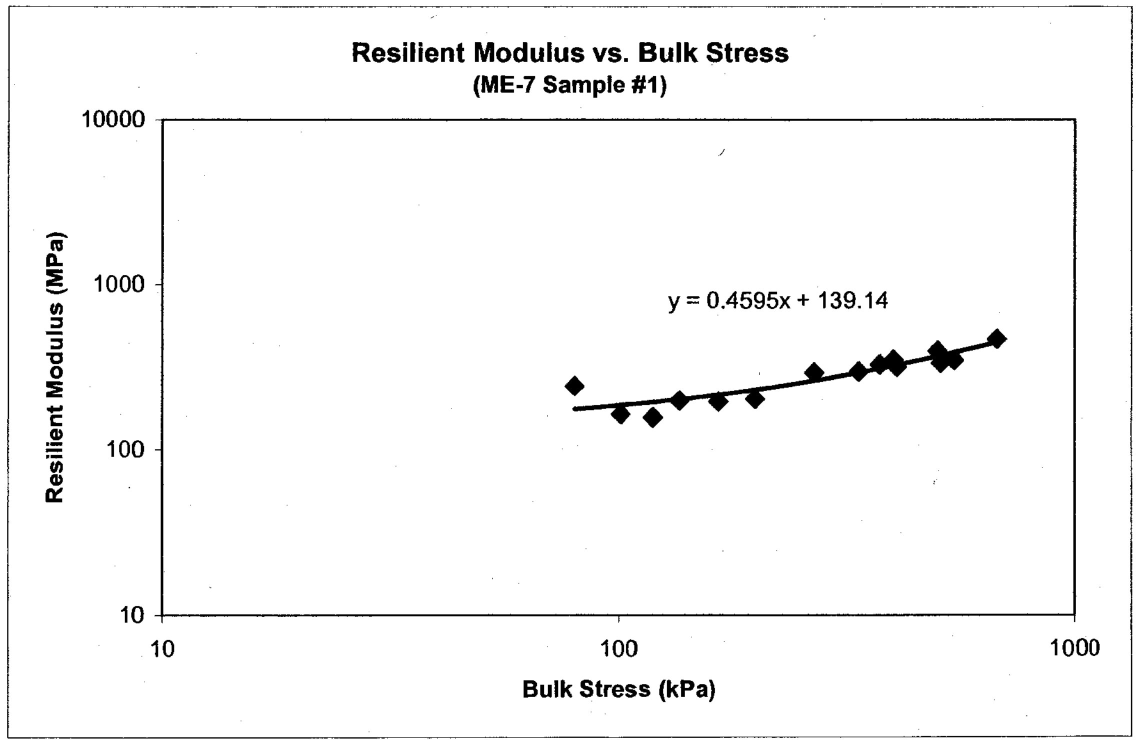
Mr Intercept Value	501.04
Mr Slope Value	0.05210
Mr @ 500 Θ (kPa)	**527.09**

Reduced Data from Testing
ME-7 Sample 1 (11 Sep 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	80.083	243.3973
2	101.377	164.1678
3	118.711	156.5606
4	135.566	197.9
5	164.699	195.2844
6	197.877	202.2522
7	267.418	292.7014
8	334.647	296.613
9	399.467	350.2821
10	372.49	327.1352
11	406.626	318.251
12	499.984	398.023
13	508.454	334.5881
14	543.82	349.5093
15	674.552	468.4002

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	130.60	122.00	30.50	9.40%
1b	133.90	124.70	30.10	9.73%



Average Moisture Content
9.5620

Specimen Weight (g)	3744.10
Specimen Height (cm)	20.50
Specimen Wet Density (lb/ft3)	140.6356
Specimen Dry Density (lb/ft3)	128.36

Average	286.3377
Median	296.613
Gmean	272.4088

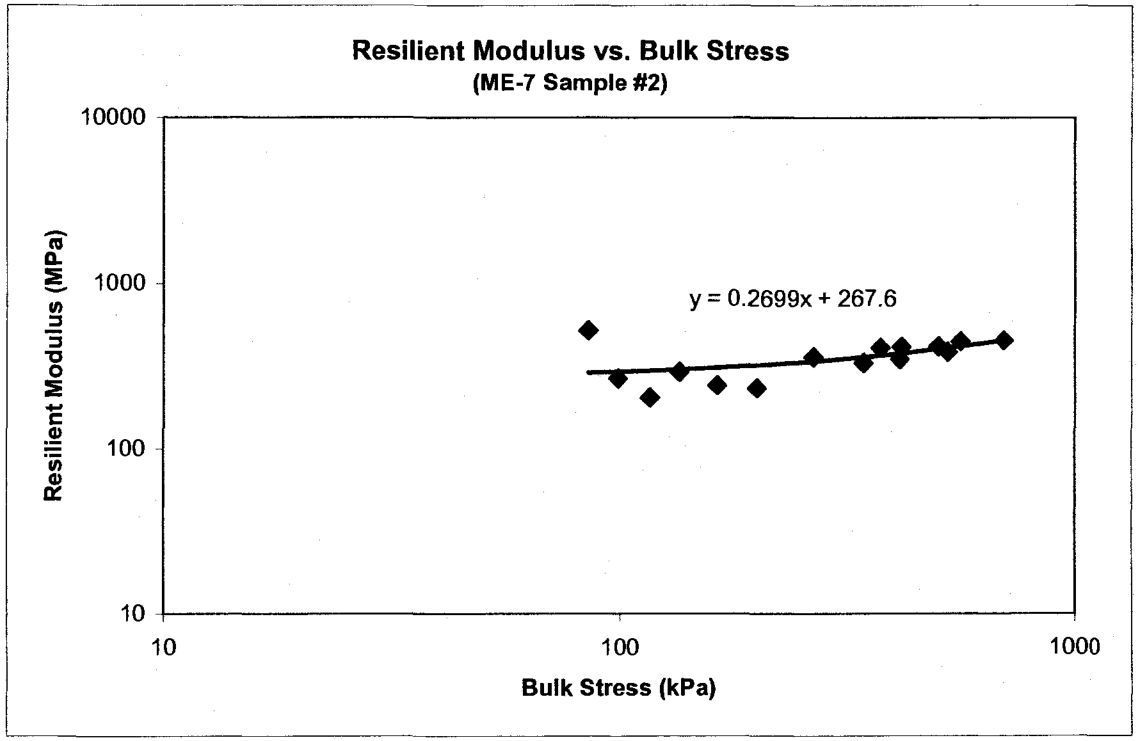
Mr Intercept Value	139.14
Mr Slope Value	0.45950
Mr @ 500 Θ (kPa)	**368.89**

Reduced Data from Testing
ME-7 Sample 2 (18 Sep 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	85.582	522.6847
2	99.22	267.962
3	116.36	202.7795
4	135.444	293.6871
5	163.727	241.2456
6	199.827	233.5133
7	266.143	359.5902
8	342.876	332.7358
9	412.945	350.841
10	373.835	410.2968
11	416.317	414.789
12	525.858	386.7428
13	501.647	416.9566
14	560.791	448.5438
15	701.275	454.7794

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	153.00	141.90	30.80	9.99%
1b	154.20	144.00	30.70	9.00%



Average Moisture Content
9.4958

Specimen Weight (g)	3682.40
Specimen Height (cm)	20.00
Specimen Wet Density (lb/ft3)	141.776
Specimen Dry Density (lb/ft3)	129.48

Average	355.8098
Median	359.5902
Gmean	343.7191

Mr Intercept Value	267.60
Mr Slope Value	0.26990
Mr @ 500 Θ (kPa)	**402.55**

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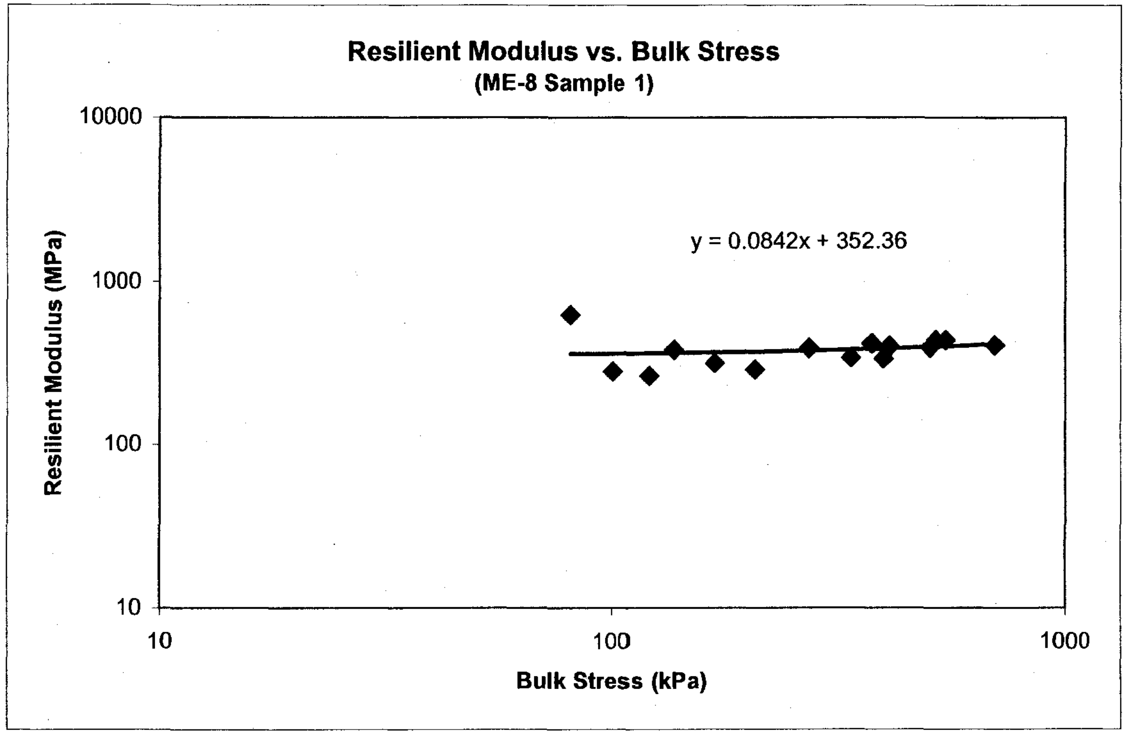
Reduced Data from Testing
ME-8 Sample1 (13 August 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	81.252	621.14808
2	101.137	280.52671
3	120.771	263.77339
4	136.98	380.08511
5	168.627	315.44519
6	206.867	286.65962
7	273.173	389.29325
8	338.459	341.28077
9	398.385	336.03048
10	375.409	413.92416
11	411.289	399.34444
12	503.28	391.67201
13	519.547	436.17887
14	546.642	435.79288
15	702.718	405.499

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	146.20	137.70	30.50	7.93%
1b	149.80	141.00	30.40	7.96%



Average Moisture Content
7.9429

Specimen Weight (g)	3508.30
Specimen Height (cm)	20.00
Specimen Wet Density (lb/ft3)	135.073
Specimen Dry Density (lb/ft3)	125.13

Average	379.7769
Median	389.2933
Gmean	371.3336

Mr Intercept Value	352.36
Mr Slope Value	0.08420
Mr @ 500 Θ (kPa)	394.46

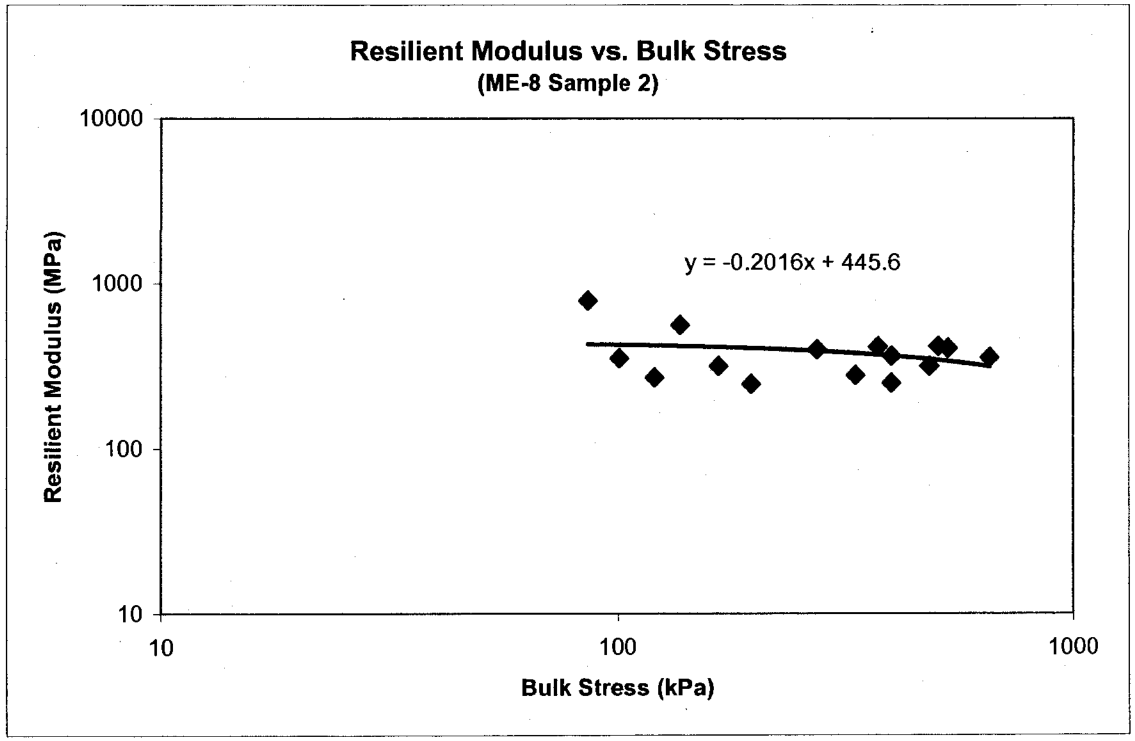
Reduced Data from Testing
ME-8 #2 (21 August 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	86.411	783.005
2	101.418	352.0871
3	120.769	268.695
4	137.54	558.9656
5	166.954	316.5
6	196.908	246.5604
7	273.642	397.3463
8	332.452	279.1983
9	397.274	250.4948
10	372.322	412.9632
11	398.075	363.6236
12	481.838	315.7099
13	503.627	418.2423
14	528.013	407.0641
15	652.259	356.1056

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	142.40	132.60	30.30	9.58%
1b	156.50	146.10	30.70	9.01%

Average Moisture Content
9.2959



Specimen Weight (g)	3569.60
Specimen Height (cm)	19.40
Specimen Wet Density (lb/ft3)	141.6836
Specimen Dry Density (lb/ft3)	**129.63**

Average	381.7707
Median	356.1056
Gmean	363.734

Mr Intercept Value	445.60
Mr Slope Value	-0.20160
Mr @ 500 Θ (kPa)	**344.8**

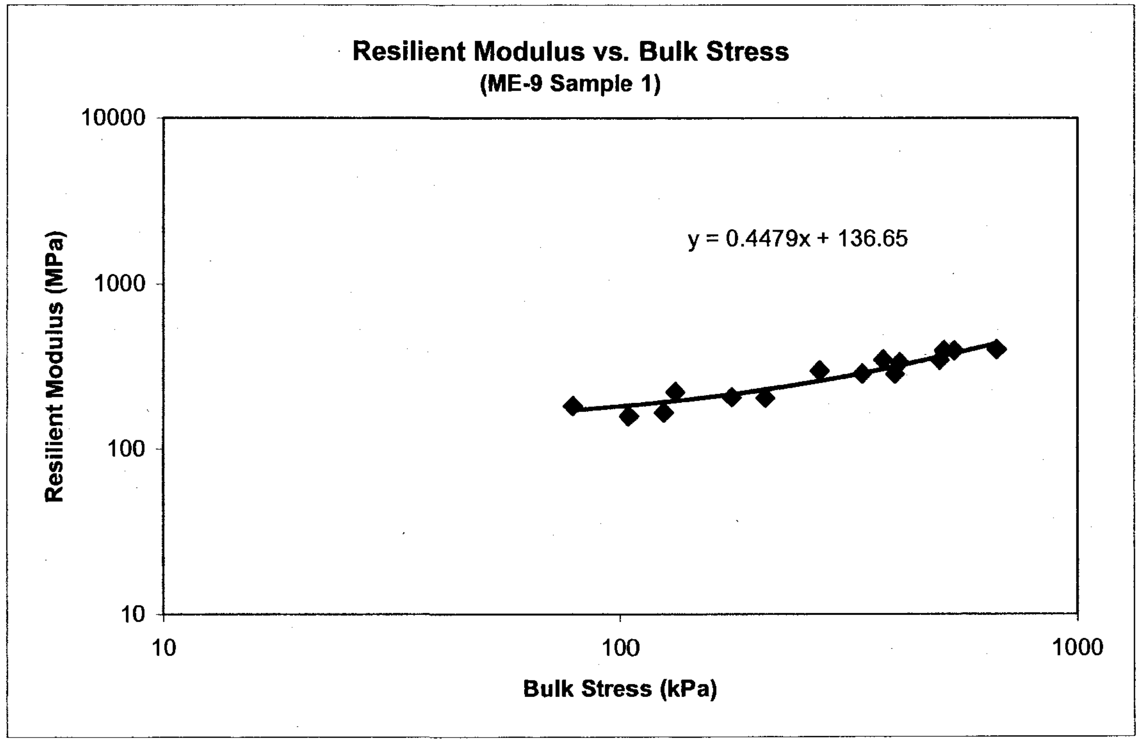
Reduced Data from Testing
ME-9 #1 (21 August 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	78.9	182.779
2	104.839	158.2497
3	124.791	165.7799
4	132.299	221.7228
5	175.569	205.3526
6	207.902	203.6306
7	272.724	298.4277
8	337.943	285.4865
9	400.324	284.9697
10	376.364	346.7204
11	410.122	333.3053
12	502.052	346.5298
13	513.256	392.9989
14	540.661	394.068
15	669.498	400.9381

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	149.30	137.40	30.50	11.13%
1b	156.30	142.60	30.40	12.21%

Average Moisture Content
11.6711



Specimen Weight (g)	3684.30
Specimen Height (cm)	19.60
Specimen Wet Density (lb/ft3)	143.9583
Specimen Dry Density (lb/ft3)	128.91

Average	281.3973
Median	285.4865
Gmean	268.2782

Mr Intercept Value	136.65
Mr Slope Value	0.44790
Mr @ 500 Θ (kPa)	360.6

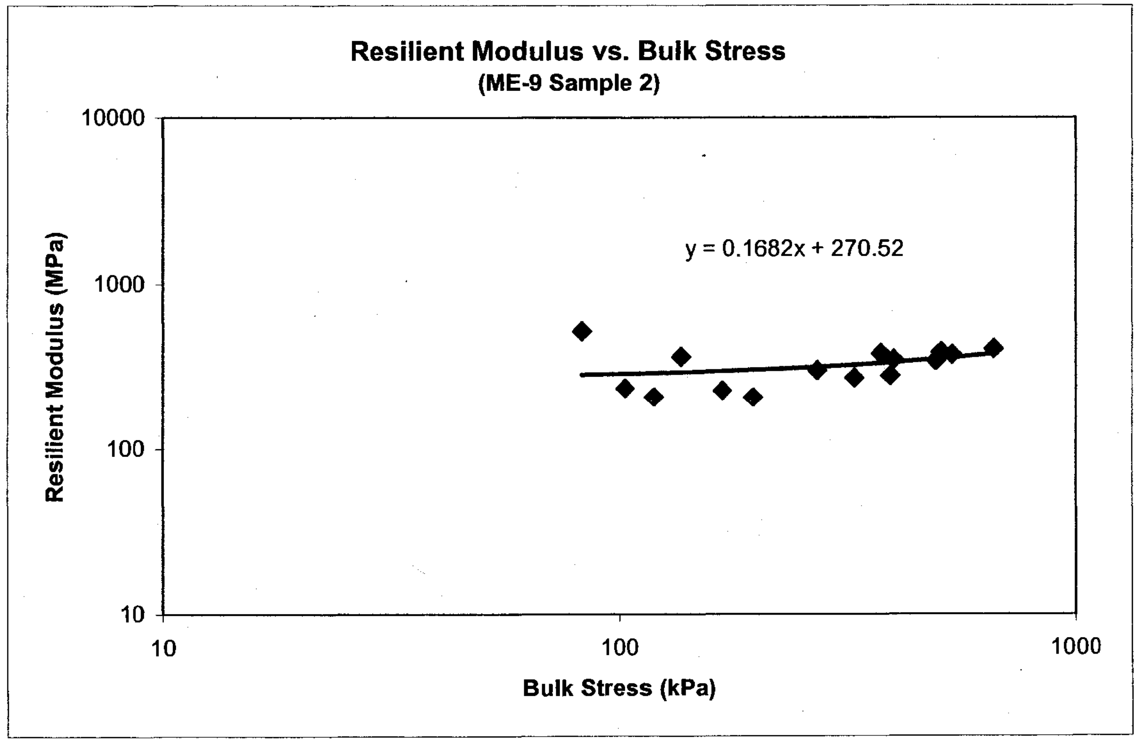
Reduced Data from Testing
ME-9 #2 (22 August 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	82.918	519.5576
2	103.291	232.9437
3	119.019	205.9508
4	136.712	364.4184
5	169.152	227.729
6	197.159	206.4776
7	274.039	301.1532
8	330.397	269.8572
9	395.605	280.764
10	377.435	381.7701
11	402.269	352.3645
12	495.715	345.4883
13	508.644	390.9226
14	537.729	377.3219
15	663.251	407.4807

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	139.80	130.00	30.50	9.85%
1b	151.60	140.70	30.10	9.86%

Average Moisture Content
9.8523



Specimen Weight (g)	3554.30
Specimen Height (cm)	19.60
Specimen Wet Density (lb/ft3)	143.9593
Specimen Dry Density (lb/ft3)	131.05

Average	324.28
Median	345.4883
Gmean	313.0853

Mr Intercept Value	270.52
Mr Slope Value	0.16820
Mr @ 500 Θ (kPa)	**354.62**

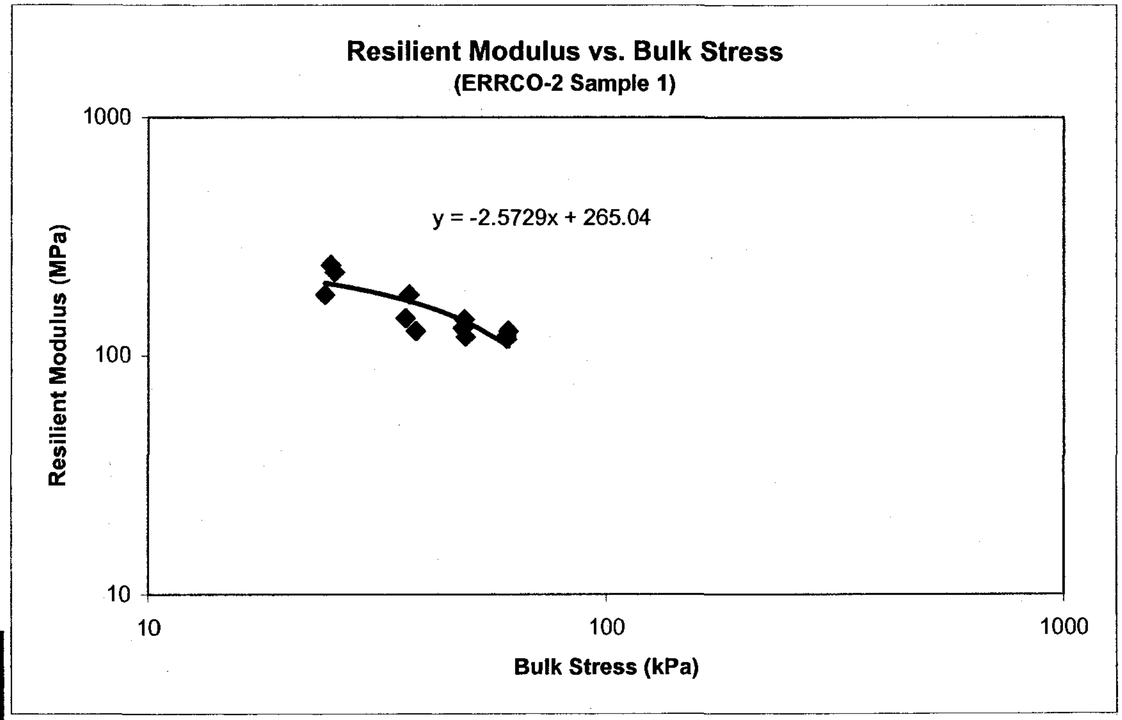
Reduced Data from Testing
ERRCO-2 #1 (6 June 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	13.666	154.7717
2	25.079	241.9008
3	36.997	181.3937
4	48.8	142.0722
5	60.743	126.7762
6	8.119	154.7717
7	25.563	225.4929
8	36.348	143.4561
9	48.419	130.3048
10	60.208	121.1276
11	8.635	154.7717
12	24.349	180.79
13	38.238	126.4861
14	49.18	120.1354
15	60.364	117.3248

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	166.10	148.30	30.80	15.15%
1b	160.60	143.30	30.60	15.35%

Average Moisture Content
15.2497



Specimen Weight (g)	3450.30
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	135.2536
Specimen Dry Density (lb/ft3)	117.36

Average	154.7717
Median	143.4561
Gmean	150.9666

Mr Intercept Value	265.04
Mr Slope Value	-2.57290
Mr @ 500 Θ (kPa)	-1021.41

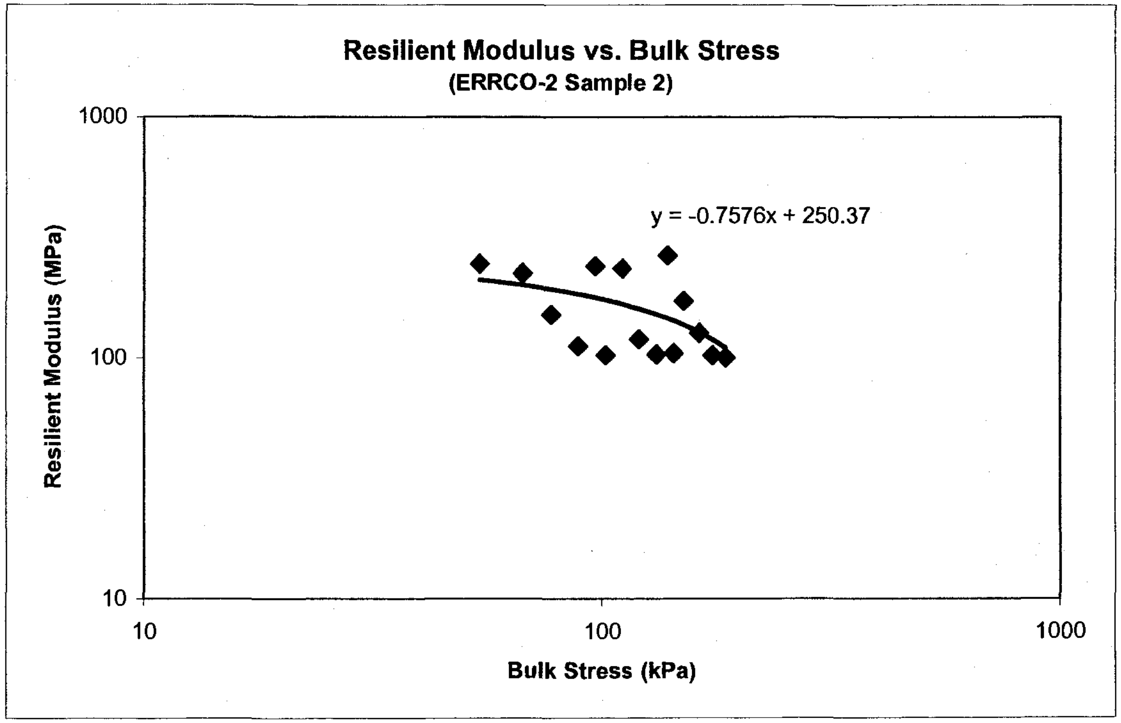
Reduced Data from Testing
ERRCO-2 #2 (10 June 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	138.336	263.5347
2	150.397	171.0334
3	162.467	126.516
4	173.534	102.46
5	185.437	100.2375
6	96.412	238.641
7	110.484	232.7576
8	120.394	118.8683
9	131.116	103.0958
10	142.942	104.2347
11	54.297	242.6131
12	67.513	222.5627
13	77.951	149.6978
14	88.975	111.7723
15	101.961	102.1318

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	167.50	148.30	30.80	16.34%
1b	161.34	143.30	30.60	16.01%

Average Moisture Content =
16.1738



Specimen Weight (g)	3640.55
Specimen Height (cm)	20.95
Specimen Wet Density (lb/ft3)	[illegible]
Specimen Dry Density (lb/ft3)	115.18

Average	159.3438
Median	126.516
Gmean	148.6778

Mr Intercept Value	250.37
Mr Slope Value	-0.75760
Mr @ 500 Θ (kPa)	**-128.43**

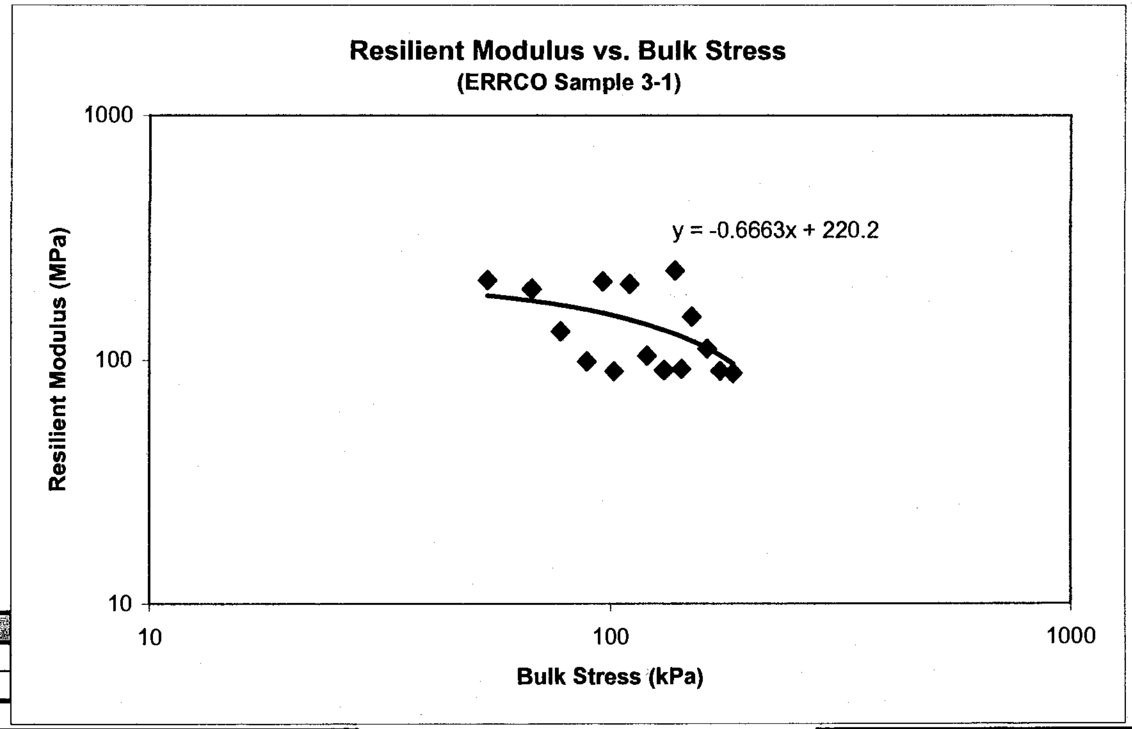
Reduced Data from Testing
ERRCO-3 #1 (10 July 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	138.336	231.7807
2	150.397	150.4252
3	162.467	111.2718
4	173.534	90.11434
5	185.437	88.15962
6	96.412	209.8866
7	110.484	204.712
8	120.394	104.5456
9	131.116	90.67352
10	142.942	91.67516
11	54.297	213.38
12	67.513	195.7456
13	77.951	131.6603
14	88.975	98.3046
15	101.961	89.82568

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	W
1a	166.10	148.30	30.80	15.15%
1b	160.60	143.30	30.60	15.35%

Average Moisture Content
15.2497



Specimen Weight (g)	3460.30
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	135.2538
Specimen Dry Density (lb/ft3)	117.36

Average	140.144
Median	111.2718
Gmean	130.7633

Mr Intercept Value	220.00
Mr Slope Value	-0.66630
Mr @ 500 Θ (kPa)	-113.15

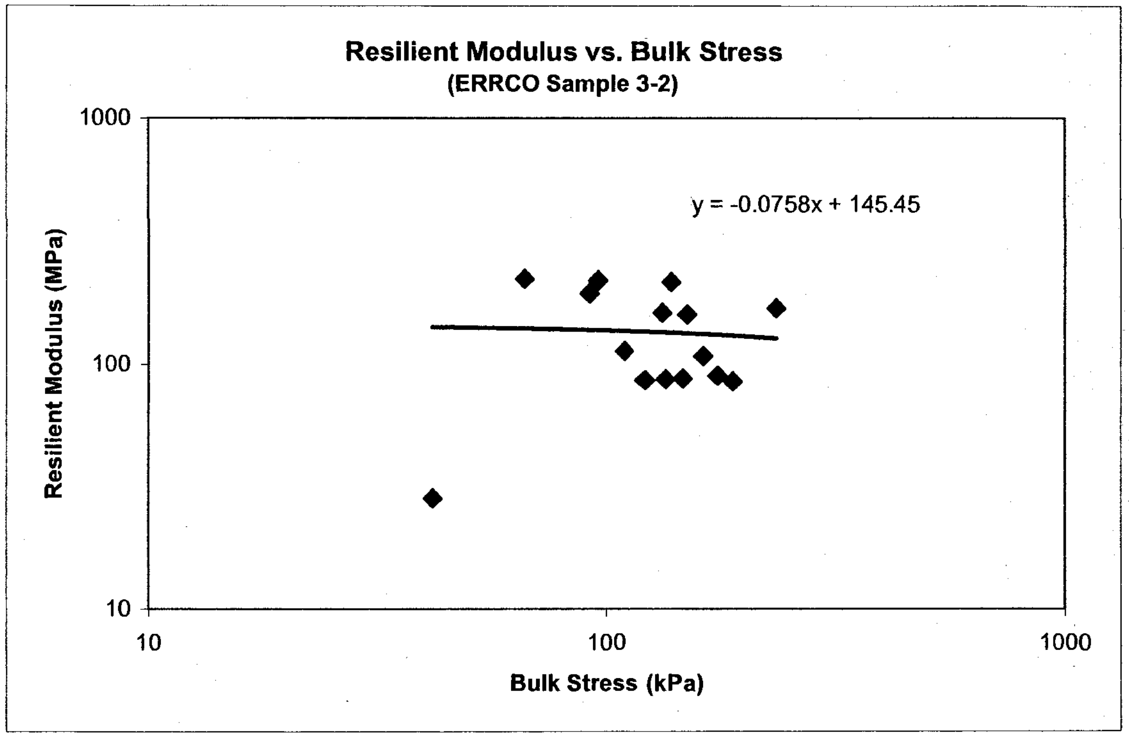
Reduced Data from Testing
ERRCO-3 #2 (21 July 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	138.287	216.961
2	149.667	159.7335
3	161.93	107.7233
4	174.072	89.53363
5	187.833	84.86049
6	96.119	220.5858
7	109.856	113.3744
8	121.593	85.78298
9	134.601	86.55012
10	146.497	87.28181
11	41.595	28.13594
12	66.327	222.9015
13	92.211	195.3738
14	132.463	162.5718
15	233.007	169.7756

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	158.45	137.40	30.50	19.69%
1b	157.25	142.60	30.40	13.06%

Average Moisture Content
16.3742



Specimen Weight (g)	3325.80
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	129.3[illegible]
Specimen Dry Density (lb/ft3)	111.71

Average	135.4097
Median	113.3744
Gmean	120.072

Mr Intercept Value	145.45
Mr Slope Value	-0.07580
Mr @ 500 Θ (kPa)	107.55

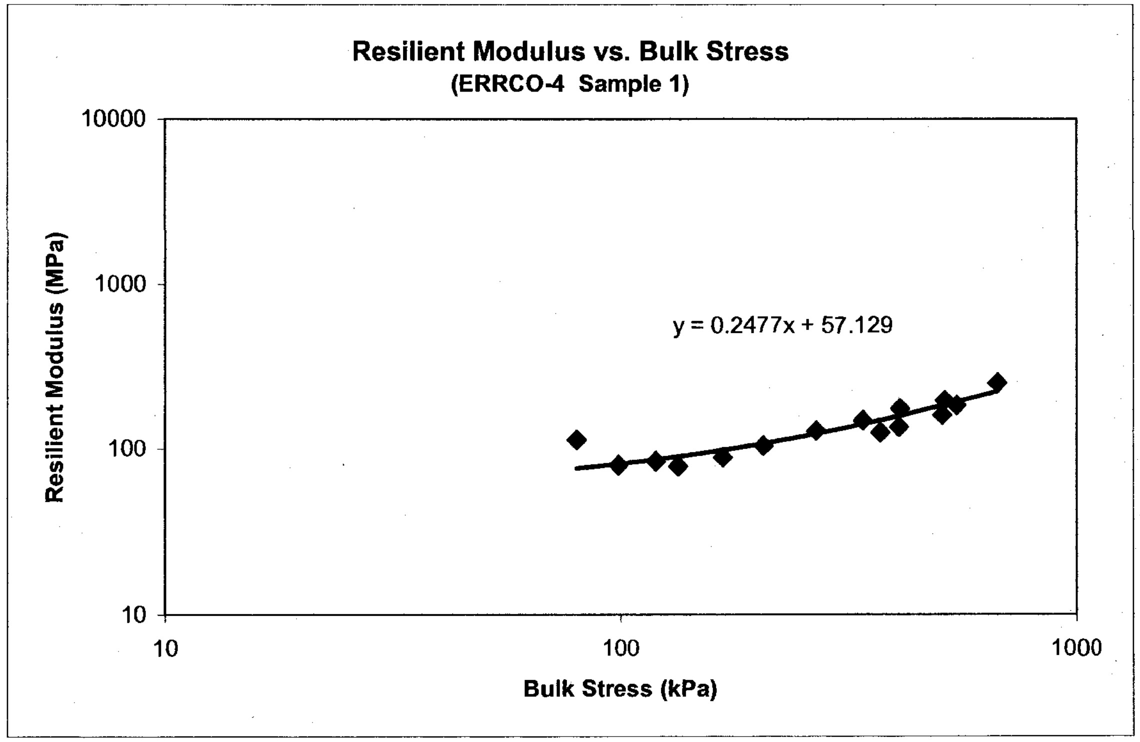
Reduced Data from Testing
ERRCO-4 #1 (13 Sept 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	80.276	113.6223
2	99.165	80.0503
3	119.701	84.3866
4	133.919	79.17679
5	167.643	89.24877
6	205.634	104.8822
7	268.574	128.4375
8	339.899	148.3861
9	410.202	175.2002
10	371.486	125.6759
11	408	135.9878
12	513.692	196.9287
13	508.282	160.3826
14	547.001	183.514
15	673.124	251.4352

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	w
1a	166.10	148.30	30.80	15.15%
1b	160.60	143.30	30.60	15.35%

Average Moisture Content
15.2497



Specimen Weight (g)	3560.30
Specimen Height (cm)	19.70
Specimen Wet Density (lb/ft3)	139.1625
Specimen Dry Density (lb/ft3)	**120.75**

Average	137.1543
Median	128.4375
Gmean	129.319

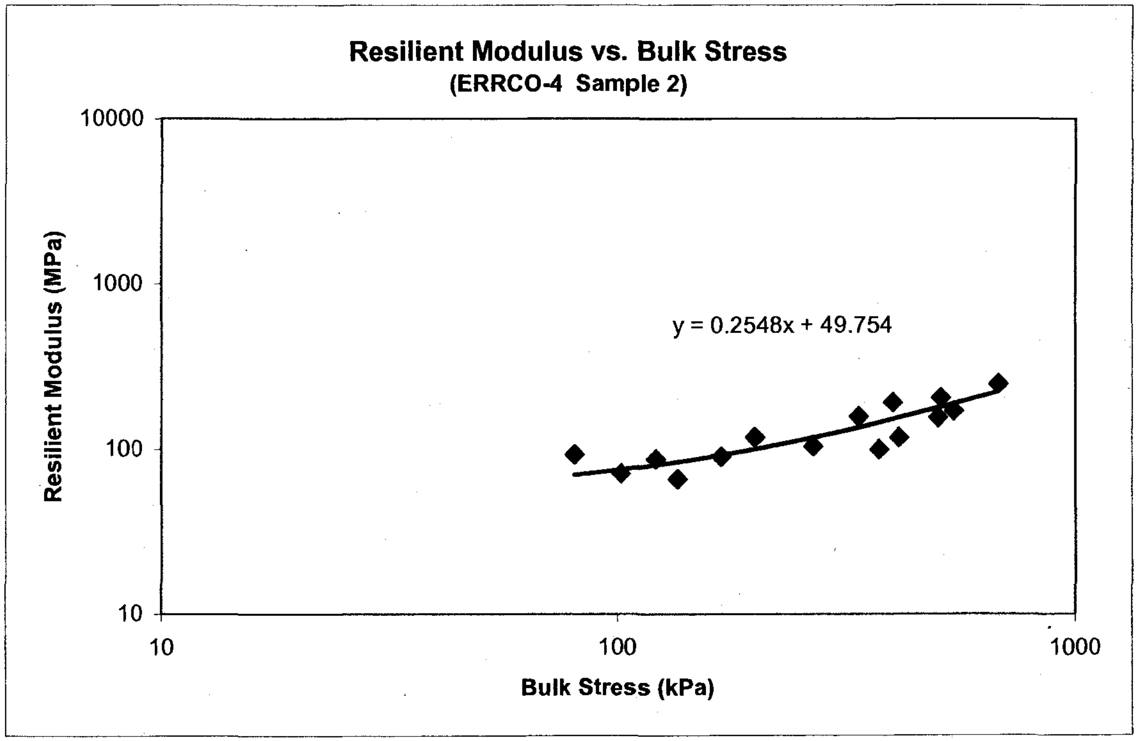
Mr Intercept Value	57.13
Mr Slope Value	0.24770
Mr @ 500 Θ (kPa)	**180.979**

Reduced Data from Testing
ERRCO-4 #2 (25 Sept 2007)

	Bulk Stress	Mr
	=(3*CP)+Sd cyc	=Mr/1000
	(kPa)	(MPa)
Iteration	θ	Mr
1	80.752	93.37943
2	102.133	71.66054
3	121.218	87.50302
4	135.209	65.794
5	168.813	90.51554
6	199.795	118.9534
7	268.726	104.8274
8	336.835	157.37
9	400.096	191.0625
10	374.302	100.193
11	412.908	117.9826
12	508.77	204.7326
13	502.583	155.3437
14	544.322	169.7644
15	680.538	249.8772

Moisture Content

Sample	W1(g)	W2(g)	Wc(g)	W
1a	151.20	134.90	30.50	15.61%
1b	140.60	128.80	30.40	11.99%



Average Moisture Content
13.8024

Specimen Weight (g)	3482.30
Specimen Height (cm)	19.50
Specimen Wet Density (lb/ft3)	137.5[illegible]
Specimen Dry Density (lb/ft3)	120.83

Average	131.9306
Median	117.9826
Gmean	122.4451

Mr Intercept Value	49.75
Mr Slope Value	0.25480
Mr @ 500 Θ (kPa)	177.154